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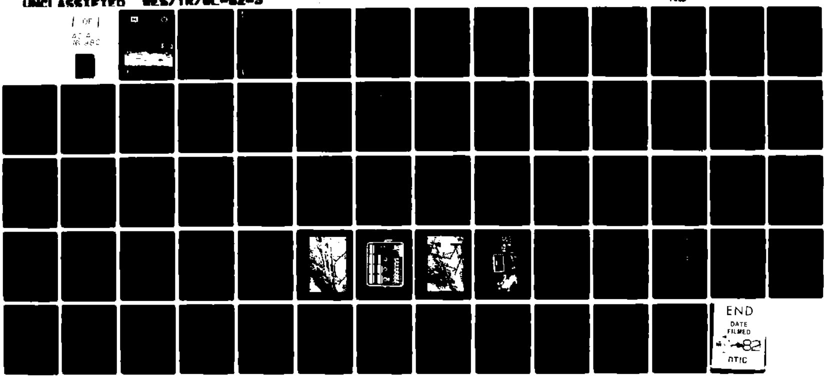

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TECHNICAL REPORT GL-82-3

NEW PRESSURE TEST FOR DETERMINING COEFFICIENT OF PERMEABILITY OF ROCK MASSES

by

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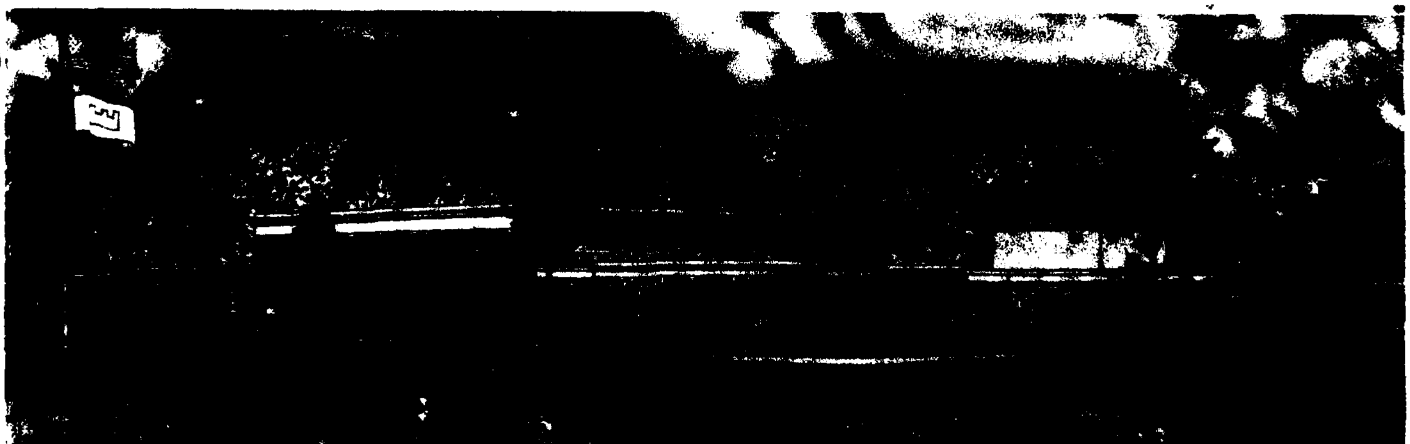
July 1982

Final Report



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New borehole pressure injection test equipment for determining the coefficient of permeability has been developed that has several improvements over equipment now in common use.

This report describes the major components of the new test equipment and the improvements made to both equipment and test procedures for reliable operation and accurate test results.

Methods of reporting, analyzing, and interpreting results are also presented.

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PREFACE

"Flow of Water Through Rock Masses," Civil Works Research and Development (CW R&D) Work Unit 31561, was initiated by the U. S. Army Engineer Waterways Experiment Station (WES) in FY 78 under the direction and sponsorship of the Office, Chief of Engineers (OCE), U. S. Army. Mr. Paul Fisher was OCE Technical Monitor.

The test equipment reported herein was developed by Mr. R. F. Anderson and Mr. W. O. Miller, Rock Mechanics Applications Group (RMAG), Engineering Geology and Rock Mechanics Division (EGRMD), Geotechnical Laboratory (GL), WES. This report was written by Messrs. R. D. Bennett and R. F. Anderson under the direct supervision of Mr. J. S. Huie, Chief, RMAG, and under the general supervision of Dr. D. C. Banks, Chief, EGRMD. Mr. J. P. Sale and Mr. R. G. Ahlvin were Chief and Assistant Chief, respectively, of GL during part of this study. Dr. W. F. Marcuson III and Dr. P. F. Hadala were Chief and Assistant Chief, respectively, during report preparation.

Commanders and Directors of WES during this study were COL John L. Cannon, CE, COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Mr. Fred R. Brown was Technical Director.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
cubic feet	0.0283	cubic metres
degrees Fahrenheit	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
foot-pounds (force) per pound (force)-degree Rankine	0.305	joules per newton-degree Rankine
gallons (U. S. liquid)	3.785	cubic decimetres
inches	2.54	centimetres
pounds (force) per cubic foot	157.1	newtons per cubic metre
pounds (force) per square foot	47.88	pascals
pounds (force) per square inch	6894.8	pascals

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

NEW PRESSURE TEST FOR DETERMINING COEFFICIENT OF PERMEABILITY OF ROCK MASSES

PART I: INTRODUCTION

Background

1. Reliable determination of rock mass permeability is essential to the design and construction of many civil engineering projects. Assessment of groundwater movement, seepage through abutments, foundation uplift pressures, and grouting requirements all depend on knowledge of the mass permeability.

2. The primary purpose of this report is to describe a new pressure injection test system and test procedures for determining the coefficient of permeability of rock masses. The pressure injection test has been widely used for over 50 years with little change in equipment or methods, although several improvements in both have been suggested. The new equipment was designed to overcome problems common to earlier equipment, such as excess head loss in the main injection line, slow packer inflation and deflation, unreliable control and measurement of pressure and flow, and packer leakage. Test procedures were improved to take advantage of the new system's measuring precision and to minimize errors or problems caused by unknowns in the test environment (e.g., partial saturation of the test zone).

3. A brief review of other methods used to measure coefficient of permeability has been included to show that there are other choices available which, under some conditions, may have advantages over pressure tests.

Laboratory tests

4. Laboratory tests of intact rock or individual fissures are convenient and relatively inexpensive compared to field tests, but the small specimens tested make their reliability suspect because of scale effects. For a typical natural rock joint the aperture variation may be of the same order of magnitude as the mean aperture. The variation of

aperture and roughness from joint to joint within the mass may often be more than an order of magnitude, and coefficient of permeability is dependent on fissure aperture, roughness, and other properties. Therefore, unless a statistically significant number of tests are run on single fissure specimens at their natural state of stress, results are unlikely to represent field flow conditions. Pipe flow analysis assumes roughness is small compared to pipe diameter. As stated above, roughness of natural fissures in rock is often of the same order of magnitude as the fissure aperture. Consequently, flow through fissured rock cannot be accurately modeled as flow through pipes, although the equivalent pipe analogy can be helpful in understanding the influence of variables such as velocity and head loss.

Aquifer pumping tests

5. Pumping tests are routinely used to determine aquifer hydraulic properties. Methods for performing and interpreting pumping tests are presented in Groundwater and Wells (1966). Solutions exist for treatment of the medium (aquifer) as a porous continuum or as a double porosity model (Wilson and Witherspoon 1970) with intact rock of low permeability bounded by fissures with much higher permeability. Saad (1967) and Gringarten and Witherspoon (1972) have presented solutions for anisotropic flow through fissured media. These solutions are applicable to flow from a cavity (pressure injection tests) as well as flow to a cavity or borehole (pumping tests). One advantage of pumping tests is that a relatively large portion of the mass is affected and the permeabilities determined more nearly represent the average flow characteristics of the aquifer. Also, the effects of turbulent flow on the determination of coefficient of permeability are much less critical for pumping out tests than for pressure injection tests. Turbulence, when it does occur, usually starts near the borehole and spreads outward in pressure injection tests. But in pumping tests, turbulence propagates into the cavity and is much less a problem because the area of infuence of the test is much larger. Disadvantages include the time required to perform tests (typically 24 hr, or much longer) and the resulting high costs. Also, only strata below the groundwater table may be tested.

And, except under ideal conditions, interpretations of results may be nonunique, requiring considerable judgment and experience by the interpreter.

Tracer tests

6. Two types of tracer tests have been used to estimate permeability. In the dilution rate method, the tracer solution is injected into a borehole and the decrease in concentration is monitored. This method requires only one borehole and may be used to determine average permeability for the entire depth of the hole. Zones of varying permeability may be identified by injecting the solution into packed off sections, using inflatable packers. Directional differences in horizontal permeability cannot be determined with this method. The travel time method requires two or more boreholes. Tracer fluid is injected into one borehole and probes are inserted into the other holes to determine when the solution arrives. Zones of varying permeability with depth may be determined if packers are used, or average permeability may be estimated. If several holes are radially located around the injection borehole, the degree of anisotropy may be assessed by measuring the different travel times. Radioisotopes, salt solutions, or fluorescent dyes may be used as the tracer solution. Lewis, Kritz, and Burgy (1966) and Maini (1971) discuss methods for determining permeability from tracer tests. Both types of tests offer advantages. Low injection pressures minimize the possibility of fissure opening which may occur during conventional pressure tests. Tracer tests can be performed more quickly than pumping tests. However, like pumping tests, tracer tests can only be used in strata below the water table. Thompson (1980) discussed some applications of tracer tests and supplied guidance for selection of tracer fluids.

Pressure injection tests

7. Sometimes called packer tests or Lugeon* tests, this test may be the only practical method for assessing permeability of strata above

* The term "Lugeon test" implies certain test details which are more restrictive than general pressure injection tests, such as specified maximum flow rate, test section length, and borehole diameter (De Mello and da Cruz 1960).

the groundwater table. Air or water may be used to pressurize the borehole test section, but water is normally used if available because of the problems involved in interpretation of air-pressure injection tests. Tests may be performed sequentially as the borehole is made, using a single-packer setup or a double-packer setup may be used in completed boreholes to determine the permeability profile. Average permeability may be obtained for a particular section or for the entire borehole length. Maini (1971) described a four-packer setup designed to minimize nonradial flow (end effects) from the test section. Pressure tests are popular because they may be performed more quickly than pumping tests and results may be used with rule-of-thumb criteria to estimate grouting requirements (Lugeon 1933 and De Mello and da Cruz 1960). Applications and limitations of pressure tests are discussed in subsequent sections of this report.

Purpose

8. This study was initiated because the Office, Chief of Engineers (OCE), recognized the need to improve Corps' capabilities for reliable measurement of coefficient of permeability, evaluation of seepage through rock abutments, and uplift under foundations of civil works structures founded on rock.

9. The equipment and test procedures described in this report incorporate improvements recommended in a previous OCE-sponsored study of rock mass permeability (Zeigler 1976) as well as improvements subsequently identified during this study.

Scope

10. A brief review of methods used to estimate coefficient of permeability of rock masses, with their relative advantages and disadvantages, has been presented in Part I. New pressure test equipment developed at the U. S. Army Engineer Waterways Experiment Station (WES) is described in Part II. (Test methods and a suggested format for

reporting results are presented in Appendix A.) In Part III, methods of analyzing and interpreting pressure test results are discussed, including field conditions for which each method is applicable. Study results are summarized and conclusions are presented in Part IV.

PART II: DESCRIPTION OF NEW PRESSURE TEST EQUIPMENT AND METHODS

Pressure Test Equipment

11. The pressure test equipment developed during this study consists of two main subsystems with several components in each:

a. The downhole system, consisting of the downhole control section, the upper and lower inflatable packers, and the screen section.

b. The surface system, consisting of the pressure and flow regulating systems and the electronic control and data readout unit.

12. The downhole and surface units are linked by a 1-1/4-in.* inside diameter (ID) by 1-5/8-in. outside diameter (OD) fluid injection line made from acme-type flush-coupled threaded tubing. An "O" ring gasket seals each joint. A single 26-conductor high-pressure electrical cable connects the downhole pressure transducers and remote control valves to the surface control and readout unit. Figure 1 is a schematic of the entire test system.

Downhole system

13. Plate 1 is a photograph of the downhole control section, upper and lower packers, and screen section. Figure 2 is a sketch of the complete downhole system assembled. The system may be used in boreholes from 3-in. NX-size to 13.75-in. in diameter.

14. Downhole control section. The downhole control section was designed to minimize the number of lines connecting the downhole system to the surface system. Fewer pipes, tubes, and wires running down the borehole mean less congestion, less chance of getting the tool stuck, and more efficient and reliable operation. The control section has three functions:

a. Inflation and deflation of the packers.

b. Packer pressure regulation.

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

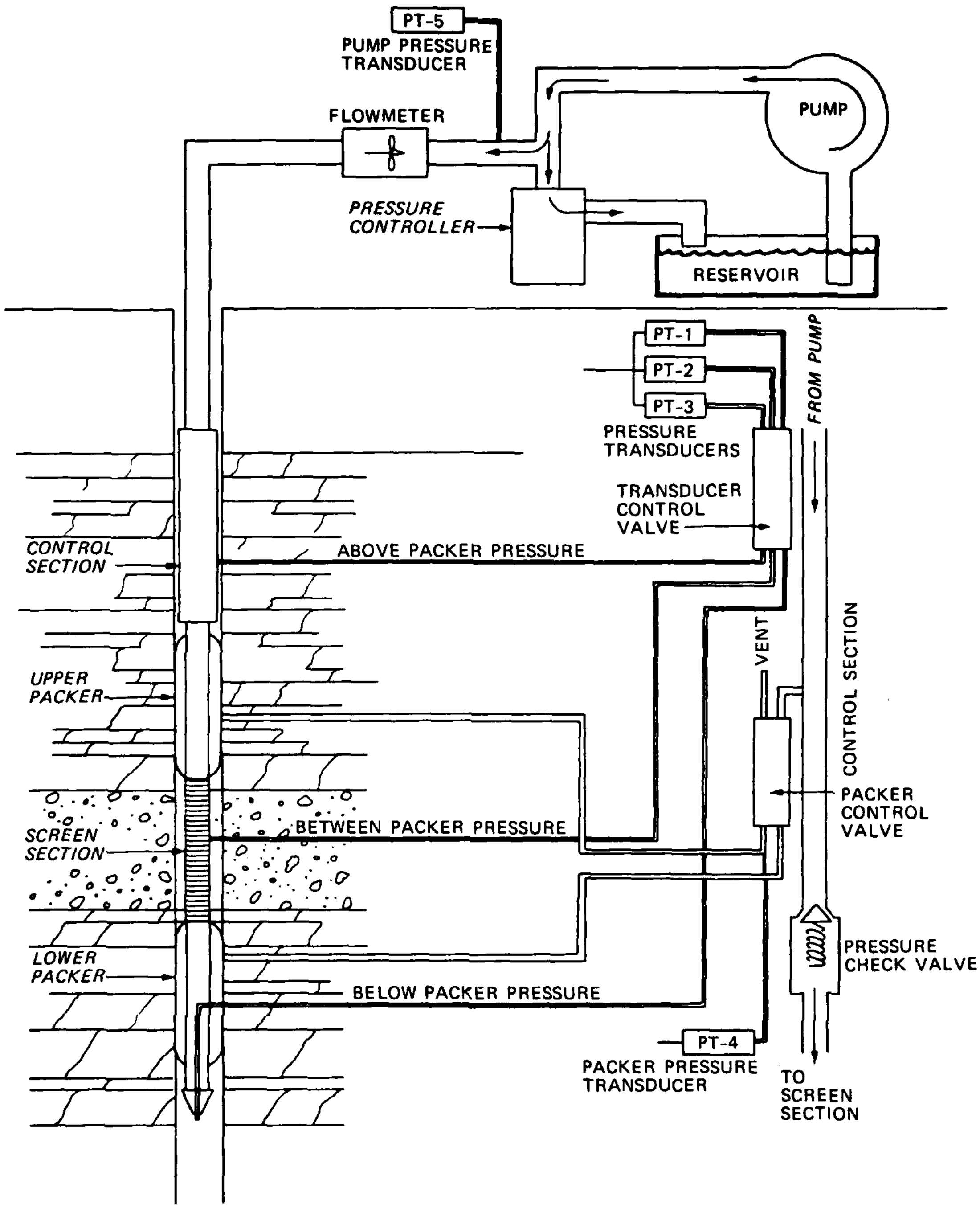

Figure 1. Schematic of entire pressure test system

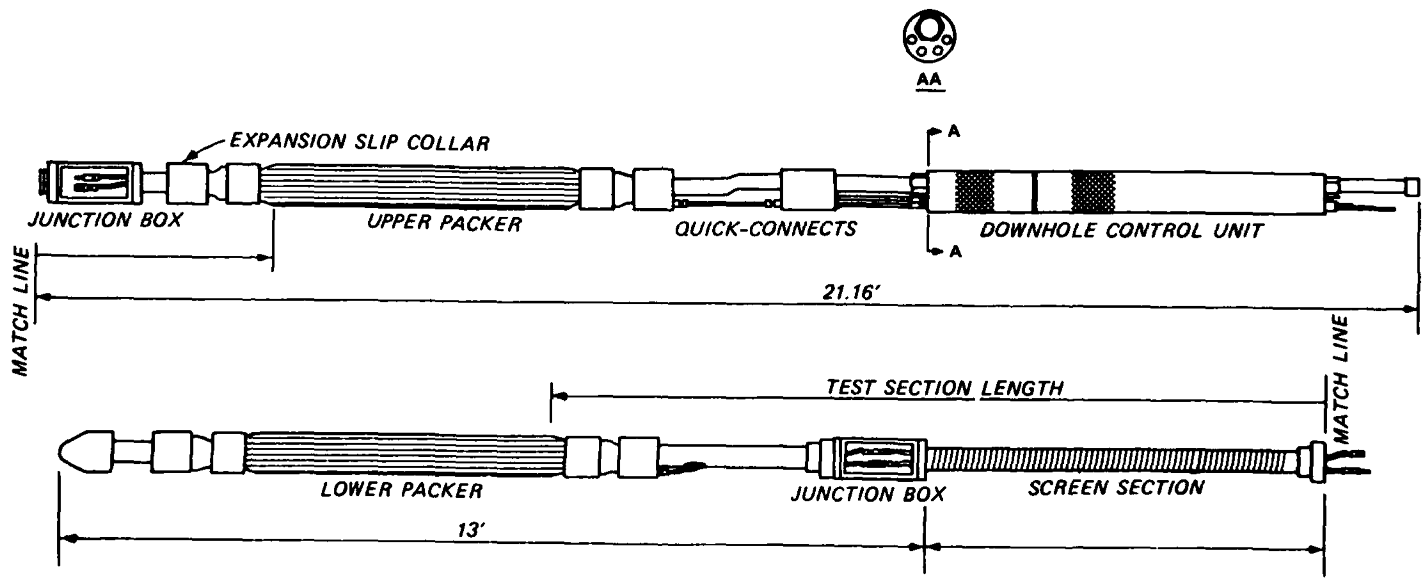

Figure 2. Complete downhole unit

c. Monitoring of borehole test section pressure, pressure above the upper packer and below the lower packer, and packer pressure. Pressure-sensing transducers monitor the various pressures, and remote-controlled valves control the inflation or deflation of the packers and connect the pressure-sensing transducers to the various pressure-monitoring points.

Packer pressure is measured by a transducer in the main 1-1/4-in. ID injection line. A constant differential pressure between the packers and test section (normally 100 psi) is maintained during tests by using a large pressure-relief valve. Fluid entering the test section from the injection line must pass through the downhole pressure-relief valve. As the pressure is increased at the surface, the packers inflate via the packer-control valve to the selected differential pressure before any fluid passes through the valve to the screened test section. Further pressure increases affect the packers and test section equally. For example, for a selected differential pressure of 100 psi and test section pressure of 50 psi, the packer pressure would be 150 psi. The packer control valve allows the operator to independently control inflation and deflation of either or both packers. Use of the pressure-relief valve and packer-control valve eliminates the need for separate packer inflation lines and greatly reduces the time required for packer inflation and deflation. Time savings can be quite significant for deep borings tested under high pressure, because of the slow packer response caused by high friction head losses in the small-diameter inflation lines used on earlier equipment. In addition, the need for manual pressure adjustments by the operator is eliminated. Packer pressure is monitored at the surface on the electronic readout unit using a downhole pressure transducer connected directly to the main pressure injection line. The other three pressure measurement points (i.e., below lower packer, above upper packer, and test section) have built-in redundancy, which allows any of the three pressure transducers to monitor any of the three measuring points. A special nine-way valve is connected to the three transducers and can be switched from one point to another at the surface control unit. This setup allows the operator to cross-check pressures and allows the test to continue, even if up to two of the transducers fail. The single 26-conductor electrical cable links the nine-way valve and three transducers to the surface control unit.

15. Packers. The packers currently used with the pressure test system were designed for use in an NX-size borehole (3-in. ID). They have a gland length of 90 in. and an uninflated diameter of 2.519 in. Maximum inflated diameter is 4.625 in. The maximum recommended working pressure is 300 psi. However, this pressure is the maximum differential working pressure between inside and outside of the packer. Therefore, inside pressure may be increased in water-filled holes, proportional to the static head. Larger-diameter, interchangeable packers are available which allow the tool to be used in boreholes with a diameter up to 13.75 in.

16. Screen. The screen section shown in Plate 1 is wire-wrapped stainless steel with a 0.080-in. keystone slot width. Screen sections are 1-3/4-in. diam and 5 ft long. Sections may be coupled to increase screen section lengths to 10, 15, or 20 ft. The wire-wrapped, stainless steel screen resists corrosion and minimizes friction head losses in the borehole test section.

Surface system

17. A photograph of the surface control and readout system is shown in Plate 2. The surface system consists of the electronic control and digital data readout unit and the flow manifold which houses the flow rate transducers and the fluid pressure regulator (shown in Plate 3).

18. Electronic control and data readout unit. Plate 2 shows the electronic control and data readout unit. The unit has seven digital display meters which show test section pressure, packer pressure, pressure above top packer, pressure below bottom packer, flow rate in gal per min, surface pump pressure, and fluid temperatures. Three rotary switches control the various tool functions. The flow rate switch on the left side of the unit's front panel (Plate 2) selects the flowmeter output to be monitored and provides a position for flowmeter calibration. The transducer switch near the center of the unit's front panel controls the nine-way pressure selector valve housed in the downhole control

system. The packer control switch controls the packer inflation/deflation valve in the downhole unit. The surface unit also contains the signal-conditioning and amplifying units needed for the pressure transducers used with the system. Binary-coded digital (BCD) outputs of all display points are provided in the control unit to allow input data to be recorded on tape, printer, or plotter. Manifold valves control fluid flow through the flow transducers. The flow transducers are turbine-type flowmeters that use inductive pick-off coils to measure water flow ranging from 0.03 to 250 gal per min. Air-flow rates between 0.15 to 750 ft^3 per min may be measured when air-pressure injection tests are run. Fluid-injection pressure is controlled with a specially fabricated pressure regulator, shown schematically in Figure 3. Constant fluid pressure is maintained by bypassing excess pump water back to the supply reservoir through a variable flow control valve. Bypass pressure is controlled from the pressure regulator on the gas cylinder. The preset pressure is applied to the Bellofram piston, which closes the flow control valve. At pressures below the bypass pressure, all flow goes to the flow manifold. At higher pressures, the Bellofram piston and flow control valve open and excess flow returns to the reservoir.

19. Constant flow rate regulator. The pressure test equipment can be operated as a constant flow rate device, if desired, by replacing the fluid pressure regulating system (Plate 3) with a servo-controlled constant flow rate unit. A schematic of the flow rate control unit is shown in Figure 4. Plate 4 is a photograph of the components which make up the unit. The turbine flowmeters provide an analog signal output proportional to the flow rate passing through them. The analog signal is fed into the differential amplifier and the power supply voltage is calibrated to equal the flow rate desired. When the amplifier input signals from the power supply and flowmeters are equal but opposite in polarity, the amplifier output is zero. If the flowmeter output voltage is greater than the power supply voltage, the differential amplifier output signal is positive. If the voltage from the flowmeters is less than the power supply voltage, the amplifier output signal is negative.

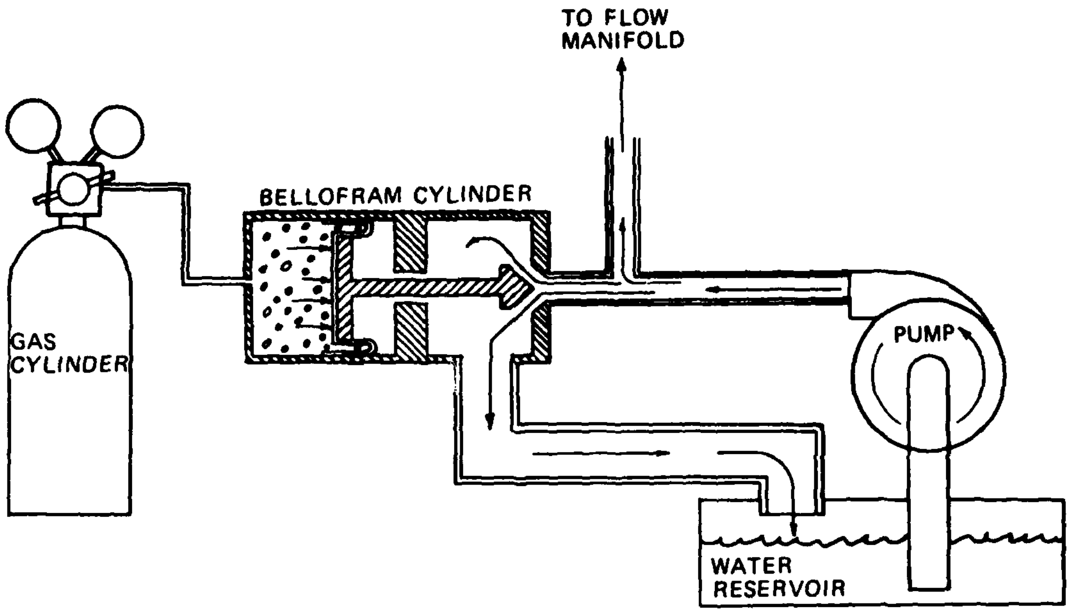

Figure 3. Schematic of pressure-regulating bypass valve

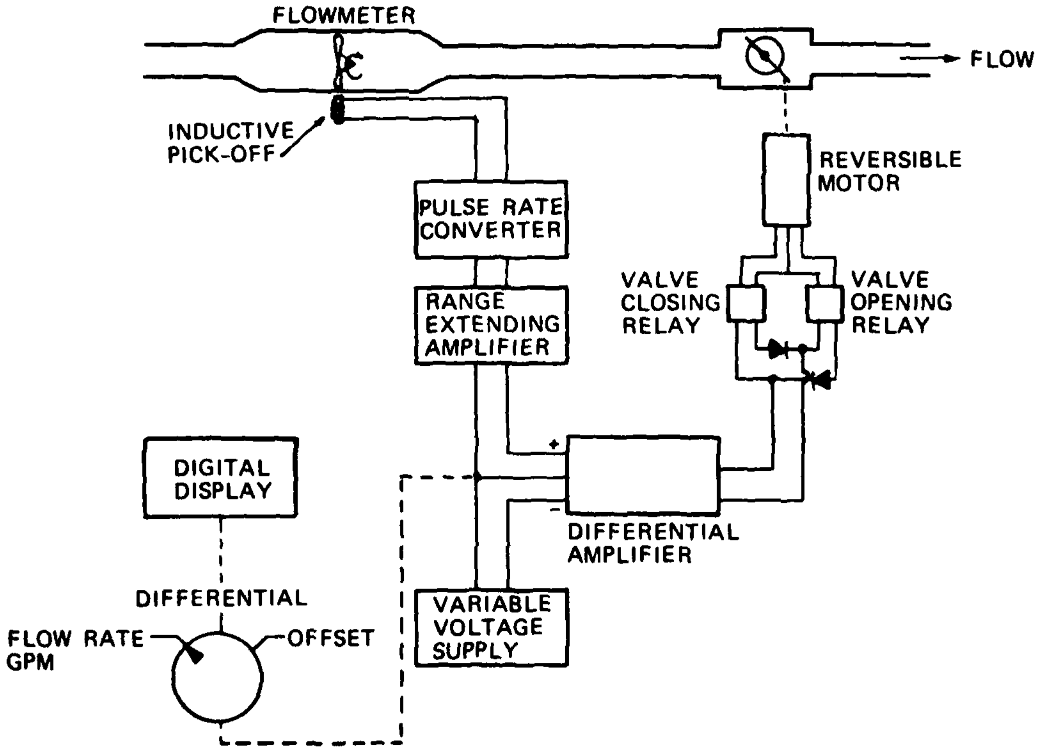

Figure 4. Schematic of flow control unit

The differential amplifier signal drives a motorized valve on the upstream side of the flowmeters. A positive amplifier signal causes the valve to close until the flowmeter input voltage equals the power supply input voltage, at which point the valve motor stops. Likewise, a negative amplifier signal causes the valve to open until equilibrium is reached.

Miscellaneous equipment

20. In addition to the major equipment components described in the preceding paragraphs, several miscellaneous tools and accessories are required to perform borehole pressure tests:

- a. Reservoir for water supply or high capacity air compressor for air-pressure tests.
- b. Pump capable of providing the required volume of flow and pressure.
- c. Hoist. A drill rig or portable tripod and hoist can be used for lowering and raising downhole unit.
- d. Stopwatch (for falling head tests).
- e. Wire ties for attaching electrical conductor cable to injection line.
- f. Electrical test equipment, such as a multimeter.
- g. Tank of pressurized air or nitrogen.

Pressure Test Methods

21. The pressure injection test consists of pumping water or air into an isolated section of borehole. The injection pressure is held constant and the flow rate is monitored until a constant limiting flow rate is reached, at which time steady-state flow is assumed. Normally, water is used if available because of the uncertainty involved in correlating results of compressible fluid (air) flow tests with incompressible fluid (water) flow parameters. (Water is slightly compressible, but the volume change is usually neglected in practice except in analysis of deep aquifers.)

22. There is no standard test method for performing pressure tests, but suggested methods are described in Civil Works Construction

Guide Specification, CE-1201 (U. S. Army, Office, Chief of Engineers 1961), in the Rock Testing Handbook, (U. S. Army Engineer Waterways Experiment Station 1980 (Standard 381-80)), and in "Determination of Rock Mass Permeability" (Zeigler 1976). Procedures for constant and falling head tests, as well as three-cell injection tests, are described in "Suggested Methods for Determining Hydraulic Parameters and Characteristics of Rock Masses," Category II, Part 6, prepared by members of the International Society of Rock Mechanics Commission on Standardization of Laboratory and Field Tests (Louis 1977).

23. The methods described in Appendix A were adopted partly from the suggestions and recommendations contained in the above references with modifications as required for use with the specific test equipment developed during this study. Detailed instructions are given for carrying out single- or double-packer pressure tests using water or air injected under constant or falling head conditions.

PART III: ANALYSIS AND INTERPRETATION OF RESULTS

24. Correct interpretation of pressure test results depends on the validity of the assumptions and boundary conditions used in the analysis. Too often, unfortunately, particular equations of flow are indiscriminately applied without considering whether the underlying assumptions and boundary conditions are reasonably satisfied by the actual field conditions. The following paragraphs present solutions that have been developed by previous researchers for various field conditions for flow of water and air through rock. Appropriate boundary conditions, assumptions, and limitations are given for each case. In all cases, a vertically oriented cylindrical borehole test section is assumed. Test results from inclined boreholes may be easily transformed to horizontal and vertical components, if desired, or the directional flow rates can be used as measured.

Continuum Approach

Laminar flow

25. Analysis of flow of an incompressible fluid through saturated rock or soil is usually made assuming Darcy's law to be valid, i.e., a linear relationship exists between hydraulic gradient and flow velocity. Flow is assumed to occur uniformly throughout the mass rather than through individual fissures. The coefficient of permeability thus determined is called the equivalent coefficient of permeability. The conditions which must be met for this approach to be valid are:

- a. Rock mass is homogeneous, isotropic, and saturated.
- b. All flow is radial and axisymmetric about the borehole.
- c. Borehole test section is vertical.
- d. Flow is steady state.
- e. Flow is laminar.
- f. Linear relationship exists between pressure and flow rate. (Darcy's law is valid.)
- g. There is no leakage around the packers.

h. Inertia terms are negligible, i.e., the change in pressure caused by the acceleration of flow into the mass is negligible. The importance of inertia terms can be checked by plotting test results as H/Q versus Q. The general relationship of injection pressure head, H_o, and flow rate, Q, may be expressed as:

$$H_o = AQ + BQ^2$$

Obviously, B must be zero if a linear (Darcy) relationship holds. So, if the above equation is rearranged as:

$$H_o/Q = A + BQ$$

and plotted as H_o/Q versus Q, the H/Q intercept will be at A, where A represents head loss due to friction. If the resulting plot has a slope of zero (horizontal line), then the constant $B = 0$ and the inertia effects are negligible. Indeed, turbulence, the possibility of fissure openings, or any other cause of nonlinearity such as packer leakage may be discounted if the slope is zero. If the slope is nonzero, the nonlinearity may be considered using the Missbach approach presented later, if the nonlinearity is due to turbulence. Obviously, undetected packer leakage and opening of fissures will result in erroneous results, regardless of the analytical method used.

Constant head tests

26. When conditions a through h are satisfied, the equivalent coefficient of permeability may be calculated from constant pressure test results using the equation below, derived by Hvorslev (1951):

$$K_e = \frac{Q}{2\pi L H_o} \ln \frac{R}{r_o}$$

where K_e = equivalent coefficient of permeability (LT^{-1})

Q = volume flow rate at equilibrium (L^3T^{-1})

r_o = borehole radius (L)

R = radius of influence of the pressure test, (L) (distance from borehole at which excess pressure is zero).

H_o = excess pressure head at center of test section = $\dfrac{P_t - P_o}{\gamma_w}$

L = length of test section, (L)

(Consistent units should be used for all variables.)

The test-section length, L , is the distance between inflated packers, or for single-packer tests, the distance from the bottom of the top packer to the bottom of the hole. P_t is the pressure during testing, P_o is the initial pressure measured by the electrical transducer, and γ_w is the unit weight of water. P_o is zero for tests above the groundwater table. For tests below the groundwater table, the groundwater pressure may be set to zero on the recording device. In this case, only the excess test pressure will be observed.

27. The flow rate, test-section length, excess head, and borehole radius are all known from particulars of the pressure test. However, the radius of influence is unknown. In the absence of piezometer measurements at a known distance from the test boring within the radius of influence, or when unsaturated strata are tested, the radius of influence must be estimated. In practice, an arbitrary but realistic value for R between L and $L/2$ is often assumed and justified using the argument that since the relationship between R and K_e is logarithmic, i.e., $K_e \sim \ln R$, the effect on K_e from assuming an incorrect radius of influence is not significant. For a porous continuum, R may be calculated for an aquifer of infinite areal extent using the empirical equation developed by Sichardt, (reported in Maini (1971) and Sharp (1970)): $R = 3000\ K_e\ (H_o - H_R)$ where R is in metres, K_e in cm/sec, and H_o is excess head in metres in the test section, and H_R is excess head at R $(H_R = 0)$. Since this equation contains the coefficient of permeability, K_e , a trial and error solution is required. This equation may yield a more accurate estimate of R for a porous continuum, but should be used with caution. There is no evidence to support its use in fissure flow. Generally R will be smaller in a fissured mass because head loss occurs more rapidly with distance from the hole. In tests in saturated strata, if a piezometer is located within the zone of influence, the measured excess head at the known radial distance can be used in the equation for permeability as below:

$$K_e = \frac{Q}{2\pi L\ (H_o - H_1)} \ln \frac{r_1}{r_o}$$

where r_1 = distance to piezometer

H_1 = excess head at piezometer

Note that the excess head must be determined by packing off or isolating the section of piezometer which corresponds to the same elevation as the test section. All other variables are as defined previously. The above expression yields the average permeability in a straight line from the borehole test section to the isolated section of the piezometer. Anisotropy in the horizontal plane may be investigated by monitoring piezometers at different orientations from the test hole and calculating the corresponding permeability coefficients. From these data the magnitudes and directions of principal coefficients of permeability in the horizontal plane may be determined.

Pressure drop test

28. The equivalent coefficient of permeability may be computed from pressure drop or falling head test results using the equation:

$$K_e = \frac{r_o^2}{2L\Delta t} \ln \frac{H_{o_1}}{H_{o_2}} \ln \frac{R}{r_o}$$

where K_e = equivalent mass coefficient of permeability

r_o = borehole radius

H_{o_1} = excess head in test section at time t_1

H_{o_2} = excess head in test section at time t_2

$\Delta t = t_2 - t_1$ = time between observations

R = radius of influence. The same problem in determining this value exists in pressure drop tests as in constant head tests. R may be reasonably estimated between L and $L/2$ in most cases.

All the assumptions previously listed for constant head tests must be satisfied (except that flow is not steady state during falling head tests).

Air-pressure tests

29. In the analysis of air-pressure tests, only constant head tests under linear, laminar flow conditions are discussed herein. The medium is considered as a homogeneous, isotropic, porous continuum. The coefficient of permeability is dependent on material properties of the

medium and the compressible fluid (air). The intrinsic permeability, K, of the medium is related to the laminar equivalent coefficient of water permeability, K_e, by the following equation, after Muskat (1946):

$$K_e = K \frac{\gamma_w}{\mu_w}$$

where K_e = laminar equivalent coefficient of permeability (LT^{-1})

K = intrinsic permeability (L^2)

γ_w = unit weight of water (FL^{-3})

μ_w = dynamic viscosity of water (FTL^{-2})

If the medium and fluid were both inert materials, the above relationship would be satisfactory despite differences between compressible and incompressible flow. However, in real field situations the medium and the fluid may undergo physicochemical alterations which invalidate the relationship. Davis and Dewiest (1966) observed that the water coefficient of permeability estimated from air-pressure test results could be overestimated by two orders of magnitude when testing sediments rich in certain clay minerals. Therefore, the following methods for calculating equivalent laminar water coefficient of permeability from air-pressure tests are offered with the above-mentioned cautions in mind. The data needed are:

a. Test section length, L

b. Borehole radius, r_o

c. Atmospheric pressure, P_a

d. Absolute pressure in test section, P_t = transducer pressure

e. Dynamic viscosity of air μ_a. It can be assumed that $\mu_a = 3.8 \times 10^{-7}$ lb-sec/ft^2 which is the viscosity at 68°F; μ_a varies over a narrow range (3.5×10^{-7} to 4.5×10^{-7} lb-sec/ft^2) between 0-250°F, respectively.

f. The weight flow rate, Q_{wf}, entering the manifold:

$$Q_{wf} = Q_m \gamma_{a_m} = Q_m \frac{P_m}{R_g T_m}$$

where Q_m = volume flow rate at the manifold (L^3T^{-1})

γ_{a_m} = unit weight of air at manifold (FL^{-3})

P_m = absolute pressure at the manifold (FL^{-2})

R_g = 53.3 ft-lb/lb-deg Rankine

T_m = absolute temperature at the manifold (deg Rankine)

Degrees Rankine = Degrees Fahrenheit + 460

g. The unit weight of air in the test section, γ_{a_t}, which is

$$\gamma_{a_t} = \frac{P_t}{R_g T_t}$$

where P_t = absolute pressure in test section, lb/ft^2

T_t = absolute temperature in test section, deg Rankine

If isothermal expansion of an ideal gas is assumed, the intrinsic permeability K may then be calculated as:

$$K = \frac{Q_{wf}\ \mu_a}{\pi L\ \gamma_{a_t}} \ \frac{P_t}{P_t^2 - P_a^2}\ \ln R/r_o$$

If the pressure transducer is zeroed downhole, then the measured pressure is the excess test pressure, and the equation reduces to

$$K = \frac{Q_{wf}\ \mu_a}{\gamma_{a_t}\ \pi L\ P_t}\ \ln R/r_o$$

and substituting for the relationship between equivalent coefficient of permeability, K_e, and intrinsic permeability, K, the equivalent coefficient of permeability is

$$K_e = \frac{\gamma_w}{\mu_w}\ \frac{Q_{wf}\ \mu_a}{\gamma_{a_t}\ \pi L\ P_t}\ \ln R/r_o$$

or rearranging,

$$K_e = \frac{\gamma_w\ \mu_a\ Q_{wf}}{\gamma_{a_t}\ \mu_w\ \pi L\ P_t}\ \ln R/r_o$$

Turbulent flow

30. Louis (1969) discussed the concept of turbulent permeability and a method for determining whether flow is turbulent or laminar. First, the pressure test results from a series of tests in one location at different excess pressures and flow rates are plotted on log-log scale as H_o versus Q. Next, a straight line is fitted to the data. The slope of this straight line is the degree of nonlinearity, m. Its value lies between 1 and 2. When $m = 2$, fully turbulent flow may be assumed. If this nonlinearity is caused by turbulent flow, the Missbach (Missbach 1937) equation may be used to calculate turbulent coefficient of permeability, K_e', from constant head tests as below:

$$K_e' = \left(\frac{Q}{2\pi L}\right)^m \frac{(R^{1-m} - r_o^{1-m})}{H_o\ (1 - m)}$$

The turbulent coefficient of permeability should be calculated from H and Q coordinates taken from the log-log straight line approximation rather than from actual data points.

31. The Forcheimer general solution for turbulent flow (Forcheimer 1914) could also be used to determine turbulent coefficient of permeability. Maini (1971) reported good correlation between the Forcheimer solution and field results for pressure versus flow rate. However, the Forcheimer solution is more difficult to manipulate mathematically to obtain a solution for flow into or out of a cavity and the generalized permeability factor is not easily determined.

32. Sharp (1970) emphasized that the turbulent permeability concept is only valid for fully turbulent conditions throughout the zone of influence of the test. He showed that for rough natural fissures a region of nonlinear laminar flow existed, as well as a smooth transition zone prior to the onset of fully turbulent conditions. In addition, if nonlinearity is caused by fissure opening or packer leakage, the turbulent flow approach will not reduce the error in calculated coefficient of permeability. Sharp concluded that unless definite proof of fully turbulent conditions existed, the calculation of turbulent coefficient of permeability could introduce additional errors rather than correct existing ones.

Discontinuum Approach

33. In the discontinuum approach of analyzing flow through rock, the mass is modeled as a system of blocks of low or negligible permeability bounded by planar joints with much higher permeability than the intact mass. The spacing and aperture of all joints intersecting the borehole test section must be considered. In addition, the effects of secondary joint systems, i.e., those joints which do not intersect the borehole but do cross the primary joints, must be considered. Pressure losses occurring at these intersections and flow occurring through these connecting conduits can be important in some cases.

34. Solutions for both laminar and turbulent flow are presented which allow calculation of coefficient of permeability from constant head test results. The solutions presented for coefficient of permeability from falling head tests and air-pressure tests are for laminar flow only. No solution is presented for turbulent flow because of the inconsistencies noted by Sharp, mentioned previously, and because the degree of nonlinearity, m , is not constant over the entire range of test pressures in falling head tests. The author is unaware of a verifiable relationship between turbulent compressible fluid flow and incompressible turbulent fluid flow.

35. It is convenient to first consider flow through a single fissure and then develop the case for flow through multiple fissures.

Laminar flow through fissures

36. Flow through fissures has generally been modeled using the smooth parallel plate analogy after Snow (1965) and Wilson and Witherspoon (1970). Radial flow governed by Darcy's law is assumed and flow is assumed to occur only through the fissures intersecting the borehole test section.

37. Experiments have been conducted (Louis 1969) to determine the range of application of the parallel plate flow model to flow through fissures. Louis defined a dimensionless surface roughness index, S , as

$$S = y/2d$$

where y = average height of fissure asperities

d = average aperture of the fissure

His tests on concrete slabs indicated that the parallel plate model gave satisfactory results for $S \leq 0.033$. For $S < 0.033$, the actual measured aperture of the fissure could be used to calculate coefficient of permeability.

Constant head tests

38. For constant head tests on single fissures the coefficient of permeability, K_j , is

$$K_j = \frac{d^2 \gamma_w}{12\mu_w}$$

where γ_w = unit weight of water

μ_w = dynamic viscosity of water

For values of $S > 0.033$, fissure roughness is important and can be considered by calculating an equivalent parallel plate aperture. This calculated aperture is not a measure of actual separation distance between two rock blocks but is the aperture separating two smooth parallel plates which would yield a flow rate equal to the observed flow rate through the natural fissure. This equivalent aperture, e , is calculated as

$$e = \left[\frac{Q}{2\pi H_o} \left(\frac{12\mu_w}{\gamma_w} \right) \ln R/r_o \right]^{1/3}$$

where Q = observed steady-state volume flow rate

H_o = excess head in test section

R = radius of influence

r_o = borehole radius

γ_w and μ_w are as defined above

Coordinate values of H_o and Q should be taken from a straight-line approximation of H_o versus Q which must pass through the origin. The radius of influence is the only unknown test variable and can be estimated with reasonable accuracy between $L/2$ and L , where L is the test-section length. This done, the equivalent parallel plate coefficient of permeability, K_{ej} , may be calculated as below:

$$K_{ej} = \frac{e^2 \gamma_w}{12\mu_w}$$

If the borehole test section is intersected by several fissures, the single-fissure analogy may be extended to allow determination of the coefficient of permeability using either of two methods. First, if the number of joints and the aperture of each joint intersecting the test section are known and if $S < 0.033$, the coefficient of permeability of the fissure system, K_s , may be calculated as

$$K_s = \frac{\gamma_w}{12\mu_w} \sum_{i=1}^{n} d_i^2$$

where n = number of fissures

d_i = aperture of an individual fissure

All other variables are as previously defined.

39. The obvious difficulty in applying this equation is the measurement of fissure apertures and the evaluation of the surface roughness index, S . The number of fissures intersecting the test section may be determined from inspection of the boring log, core samples, and where available, borehole TV or camera survey results. However, even when the fissure aperture can be measured at the borehole wall, there is little justification in using this measurement as the average aperture over the area of the fissure influenced by the test. Borehole wall disturbance may cause the aperture to be much larger at the free face due to chipping of the intact rock around the fissure. On the other hand, cuttings may seal the fissure and restrict or prevent the flow from entering the fissure.

40. Consequently, the approach normally used is to compute an equivalent parallel plate aperture, e , of each fissure as below:

$$e = \left[\frac{1}{n} \frac{Q}{2\pi H_o} \left(\frac{12\mu_w}{\gamma_w} \right) \ln R/r_o \right]^{1/3}$$

where all variables are as previously defined.

41. The equivalent laminar coefficient of permeability of each fissure is then:

$$K_{ej} = \frac{Q}{2\pi neH_o} \ln R/r_o$$

If the right-hand side of the equation is multiplied by

$$\frac{e^3}{\frac{Q}{2\pi nH_o} \; \frac{12\mu_w}{\gamma_w} \; \ln \frac{R}{r_o}}$$

the equation becomes

$$K_{ej} = \frac{e^2\gamma_w}{12\mu_w}$$

as shown previously, and the equivalent fissure system coefficient of permeability is given by

$$K_{es} = n\left(\frac{e^2\gamma_w}{12\mu_w}\right)$$

<u>Pressure drop test</u>

42. In a discontinuum analysis of pressure drop tests of natural fissures, the coefficient of permeability of a single fissure, K_j , may be calculated as

$$K_j = \frac{r_o^2}{2d\Delta t} \ln\left(\frac{H_{o_1}}{H_{o_2}}\right) \ln R/r_o$$

where r_o = borehole radius

R = estimated radius of influence

d = aperture of fissure

H_{o_1} = excess head at center of test section at time t_1

H_{o_2} = excess head at center of test section at time t_2

Δt = elapsed time between t_1 and t_2

This expression may be extended to consider multiple fissures in a test section by replacing the aperture of the single fissure, d , with the cumulative aperture of all fissures intersecting the test section, as shown below:

$$K_s = \frac{r_o^2}{2\Delta t \sum_{i=1}^{n} d_i} \ln \left(\frac{H_{o_1}}{H_{o_2}}\right) \ln R/r_o$$

43. Again, the difficulty of accurately determining the aperture of fissures and the surface roughness index, S , usually leads to the use of the equivalent aperture approach, as explained previously. If the number of fissures, n , intersecting the test section is known, the equivalent aperture, e , may be calculated as

$$e = \left(\frac{r_o^2}{2n\Delta t} \frac{12\mu_w}{\gamma_w} \ln \frac{H_{o_1}}{H_{o_2}} \ln R/r_o\right)^{1/3}$$

The equivalent aperture may then be substituted into the equation to calculate equivalent fissure coefficient of permeability, K_{ej} , as shown below:

$$K_{ej} = \frac{r_o^2}{2\Delta tne} \left(\ln \frac{H_{o_1}}{H_{o_2}}\right)\left(\ln R/r_o\right)$$

The coefficient of permeability of the fissure system is then:

$$K_{es} = nK_{ej}$$

or

$$K_{es} = \left(\frac{r_o^2}{2\Delta te} \ln \frac{H_{o_1}}{H_{o_2}} \ln R/r_o\right)$$

where all variables are as previously defined. The assumptions and conditions which must be met for these equations to apply are identical to those for constant head tests given previously except flow is not steady state.

Air-pressure tests

44. The same assumptions and conditions stated in developing the solution for computing equivalent coefficient of permeability from air-pressure test results apply to the determination of fissure coefficient of permeability. The only difference in the equation is that the effective test section length, L , in the continuum approach is replaced by the effective test section length, ne , for fissure flow, where:

n = number of fissures intersecting the test section

e = equivalent fissure aperture, assumed constant for all fissures

Therefore, the coefficient of permeability of the fissure system may be calculated as

$$K_{es} = \frac{\gamma_w \ \mu_a \ Q_{wf}}{\gamma_{a_t} \ \mu_w \ \pi n e P_t} \ \ln R/r_o$$

where all variables are as previously defined.

Turbulent fissure flow

45. If flow is turbulent rather than laminar, the Missbach equation again can be used to determine coefficient of permeability of a single fissure or system of fissures. The same precautionary notes as mentioned previously should be kept in mind. The degree of nonlinearity, m , is determined exactly as in the continuum approach discussed previously and is equal to the slope of the log H_o versus log Q straight line approximation. When evaluating coefficient of permeability, H_o and Q coordinates should be taken from the straight line of best fit and not from actual data points.

Constant head tests

46. For constant head tests, the resulting equation for equivalent turbulent fissure coefficient of permeability is

$$K'_{ej} = \frac{1}{n} \left(\frac{Q}{2\pi e} \right)^m \frac{(R^{1-m} - r_o^{1-m})}{H_o \ (1 - m)}$$

where K'_{ej} denotes equivalent turbulent coefficient of permeability of a single fissure. The equivalent turbulent coefficient of permeability of the fissure system is

$$K'_{es} = nK'_{ej}$$

or

$$K'_{es} = \left(\frac{Q}{2\pi e}\right)^m \frac{(R^{1-m} - r_o^{1-m})}{H_o\ (1 - m)}$$

The assumptions which are relevant to the application of the preceding formulas are repeated below:

a. Vertical borehole test section of length, L, intersected by n horizontal fissures.

b. Inertia effects are neglected.

c. For laminar flow, Darcy's law is valid.

d. For turbulent flow, Missbach equation is valid.

e. Steady-state radial flow occurs only within fissures intersecting the test section. (No flow through intact rock.)

f. Aperture of individual fissures is constant.

g. For equivalent system coefficient of permeability, all fissures have equal and constant aperture.

h. Test zone is saturated.

i. Boundary conditions:

   at $r = r_o$, $H = H_o$

   at $r = R$, $H = 0$

Anisotropy--Directional Permeability

47. Although it is well recognized that the most general case of rock mass property distribution is spatially random, most references emphasize the homogeneous, isotropic case, and treat anisotropy as a special condition. Indeed, isotropic, homogeneous rock is the exception, and anisotropic, nonhomogeneous rock is the rule. Analysis of homogeneous, isotropic conditions is easier than analysis of anisotropic rock, but the added theoretical complexity can be handled and is not the reason for the lack of emphasis. Nor are the researchers ignorant of the problem, but as Maini (1971) said, "No amount of theoretical sophistication is useful unless it is possible to obtain meaningful data from

the field." Therein lies the problem. In most site investigations pressure tests are run in vertical boreholes without regard for rock structure. Since directional permeability cannot be assessed from these test results, the designer either assumes isotropy or asks for additional tests in inclined boreholes drilled to maximize intersection of one joint set and minimize intersections of other joint sets or fissures. In this way, the permeability of each joint or fissure set contributing to the overall seepage can be assessed. Another method which may be used for saturated strata is to put down vertical boreholes at different bearings from the vertical test hole within the radius of influence and monitor changes in pressure. Directional differences in horizontal permeability can then be calculated and applied in a continuum analysis. Results from the first method would be applicable in a discontinuum analysis. Continuum analysis is satisfactory for some rock conditions, such as conglomerates; porous, nonfissured rock; or highly fractured rock, but for most cases, flow is anisotropic as are the mechanical properties of the rock mass.

PART IV: SUMMARY AND CONCLUSIONS

Improvements in Test Equipment

48. New pressure test equipment and methods were developed at WES which significantly improve the reliability and accuracy of rock mass permeability measurements. Improvements include:

- a. Test pressures are monitored downhole by electrical transducers, eliminating the problem of calculating head losses in the injection line.
- b. Packers are inflated and deflated through the main injection line (1-1/4-in. ID) so packer response is much faster than if inflated with 1/4-in. ID nylon lines, common to earlier equipment. Also, there is less congestion in the borehole and less chance of getting the tool stuck in the hole.
- c. Packers are longer than those on earlier equipment, thus minimizing leakage from the test section past the seal.
- d. Transducers monitor pressures in the test section, in the packers, and above and below the packers so that if leakage does occur, it is instantly recognized.
- e. A nine-way valve and redundant transducers allow the operator to cross-check pressures and allow the test to continue, even if up to two transducers fail.
- f. Different size packers may be fitted to the screen section for testing various diameter boreholes. The minimum and maximum borehole diameters are, respectively, 3 in. and 13.75 in.
- g. Test section length may be varied by adding screen sections in 5-ft increments or by running single packer tests.
- h. The electronic surface control and readout unit allows the operator to monitor and adjust all pressures and flow rate, if desired. Provisions were made for attaching tape, printer, or plotter to record test data.
- i. Air temperatures can be monitored in the test section and at the flow manifold where flow is measured. This feature allows the operator to correct volume flow rates when performing air-pressure tests.

Improvements in Test Methods

49. Pressure test methods have been adapted for use with the new equipment which result in collection of more reliable test data. Some of the improvements have been suggested previously and some were discovered during this investigation. They include:

- *a*. Air-pressure tests should not be performed below the water table. In tests above the water table, the borehole should be air-dried prior to testing. Adsorbed water on the borehole walls can cause errors in calculated permeability coefficients of more than an order of magnitude.
- *b*. Similarly, when water-pressure tests are to be performed above the water table, the borehole should be thoroughly flushed with water to remove drill cuttings which may clog fissures and to saturate the area of influence around the cavity. Permeability determined from tests in unsaturated media may be in error by more than an order of magnitude, compared with the permeability of the same media at saturation. In unsaturated media, the hydraulic gradient is larger because water may enter air-filled voids, resulting in higher measured flow rates and thus higher permeability coefficients.
- *c*. The borehole should be filled with water to a level above the top packer before inflating the packer and starting a test. This can be accomplished by venting both packers while pumping water into the hole until the "above packer pressure" display on the surface readout unit starts to rise. Then, the packers should be inflated and the test begun. Otherwise, air may be trapped inside the test section and the measured flow rates and computed permeability coefficients will be too high.
- *d*. Several pressure tests at different excess pressures should be run at each test depth to determine a possible nonlinear pressure-flow rate relationship. Because fissure deformation (opening) may occur at high test pressures and because this deformation may be inelastic and irreversible, it is suggested that the sequence of tests should be from lowest to highest excess pressure. However, there is some justification for sequencing the tests from highest to lowest pressure if care is taken to avoid fissure opening. The advantage is that the test at maximum pressure in unsaturated rock will saturate the area of influence of all subsequent lower pressure tests.

e. Selection of maximum test pressure is very important to reliably estimate permeability. In nearly all cases, the maximum test pressure should be less than the effective overburden pressure to avoid fissure opening and possible hydrofracturing. However, in very few cases there may be justification for using test pressures higher than effective overburden pressure with the knowledge that fissure opening may occur. For example, it may be desirable to test a noncritical zone of a particular rock type at higher pressures to determine the possible influence that reservoir loading may have on permeability. For example, if a critical rock formation outcropped on the upstream side of an abutment and extended downstream some distance, the downstream noncritical section could be tested at pressures representative of the maximum pool to see what effect the increase in load caused by impoundment might have on the permeability of the critical upstream outcrop. It is obvious that hydrofracturing the abutment or dam core should always be avoided.

Significance of Radius of Influence and Test Section Length

50. Sharp (1970) varied the ratio of test section length to borehole radius and observed the variation of head loss with distance from the borehole. He assumed an isotropic homogeneous continuum and linear flow and computed head as percent of excess remaining versus distance from the borehole using a numerical model. He concluded that for test section length to borehole radius ratios greater than 100 ($L/d > 100$) flow was 80 percent orthogonal to the borehole for up to 80 percent loss in head. He further concluded that 80 percent of the head loss occurs within a distance of one-half the test section length ($L/2$) from the borehole. The permeability of the medium at distances greater than $L/2$ had little effect on the flow from the test section. Maini (1971) extended this work and concluded that in fissured rock the head loss occurred at even less distance from the borehole. Two important conclusions can be made from these findings (not new, but important, nonetheless):

a. The arbitrary choice of radius of influence, R, between L and $L/2$ is reasonable considering that most of the head loss has occurred within this zone and considering further that since coefficient of permeability is proportional to the log of radius of influence, any errors in choosing R will have only a small impact on computed coefficient of permeability.

b. Pressure test results may be applicable to only a small volume of rock surrounding the test section. Nearby cavities, impermeable boundaries, etc., may go completely undetected.

Choice of Method of Analysis

51. The choice of method of analyzing pressure tests must take into consideration the field conditions. Above all, though, the test method and equipment, method of analysis, and other pertinent information should be documented. A format for reporting results has been suggested in the Appendix on test methods.

52. The continuum approach will yield satisfactory results in soil or closely jointed or crushed rock. The discontinuum approach should be used in conditions where the rock is intersected by widely spaced or irregular fissures. Where boundary conditions such as faults, impervious sills or dikes, etc., influence seepage patterns and rates, anisotropy must be considered. An example may serve to show the need to consider the possible effects of anisotropy. Consider a dam abutment characterized by two major joint sets, neither of which are vertical or horizontal. Assume permeability coefficients of the two joint sets are not equal and that permeability of the intact rock is negligible. Assume that joint set 1 dips perpendicular to the reservoir slope and joint set 2 dips parallel to the reservoir slope as shown in Figure 5. If a vertical borehole is drilled into the abutment rock and pressure tested, the coefficient of permeability thus determined is dependent on the coefficient of permeability and orientation and spacing of each joint set as well as test section length. The coefficient of permeability measured is called the equivalent mass coefficient of permeability, K_e. Upon reservoir impoundment, the joint set 1 with coefficient of permeability K_1 will be subject to the full reservoir head above the

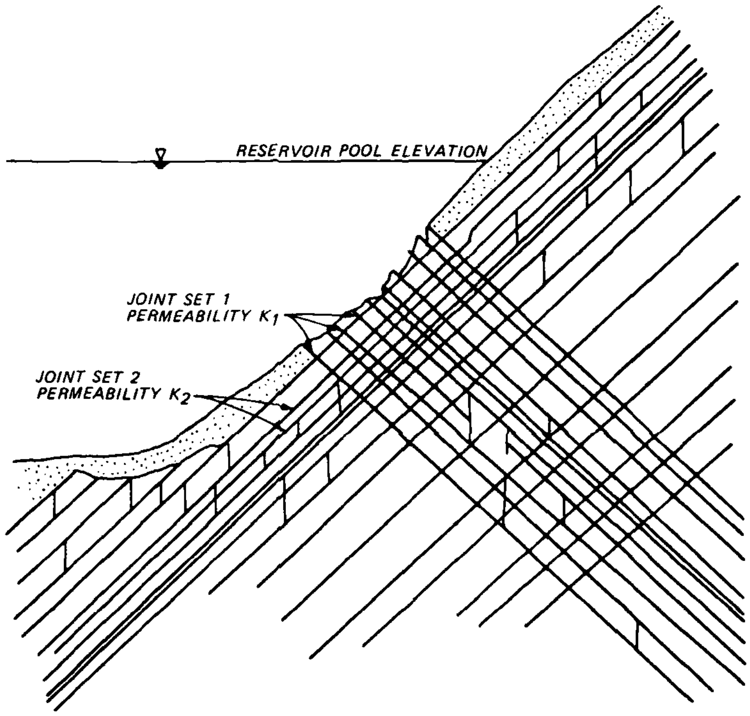

Figure 5. Intersecting joint sets

line of intersection of each joint with the reservoir free face. Therefore, the seepage rate will be controlled primarily by the flow through this joint set. Joint set 2, which does not intersect the reservoir but has strike and dip roughly parallel to the slope face, serves as an intersecting conduit for joint set 1 and has only a small effect on flow. If $K_1 >> K_2$, then the use of K_e determined in the vertical borehole would result in an underestimation of seepage. If $K_1 << K_2$, then the seepage rate would be overestimated if K_e was used in calculations. In neither case would directional flow be assessed. Another consideration is the effect of reservoir loading on the coefficients of permeability of the joint sets. It is conceivable that joint set 2 would be compressed upon impoundment, reducing the coefficient of permeability K_2 below the initial value. If initially (before impoundment) $K_2 > K_1$, then K_2 would contribute more to K_e than would K_1. However, upon impoundment K_2 might be reduced to $K_2 < K_1$, which would make K_e completely invalid.

53. Therefore, if the rock to be tested is characterized by more than one major joint set or when major features such as faults or sills are discovered, the test program should be designed to measure the coefficient of permeability of each joint set individually by testing boreholes which are intersected by a maximum number of joints in one set and a minimum number from the other set(s). Tests along the length of interest in three differently oriented boreholes will allow the complete directional permeability profile to be determined and any anisotropy will be identified. Tests performed in vertical boreholes without regard to orientation or spacing of major features may yield completely misleading results.

Consideration of Turbulent Flow

54. The concept of turbulent flow analysis, as explained by Louis (1969), relies on the existence of completely turbulent conditions throughout the zone of influence of the test. This condition may never

exist as suggested by Sharp (1970), and in any case it is nearly impossible to determine whether observed nonlinearity in the pressure-flow rate relationship is caused by turbulence or by fissure opening (or clogging) or packer leakage. Therefore, the equivalent turbulent coefficient of permeability concept should be used cautiously.

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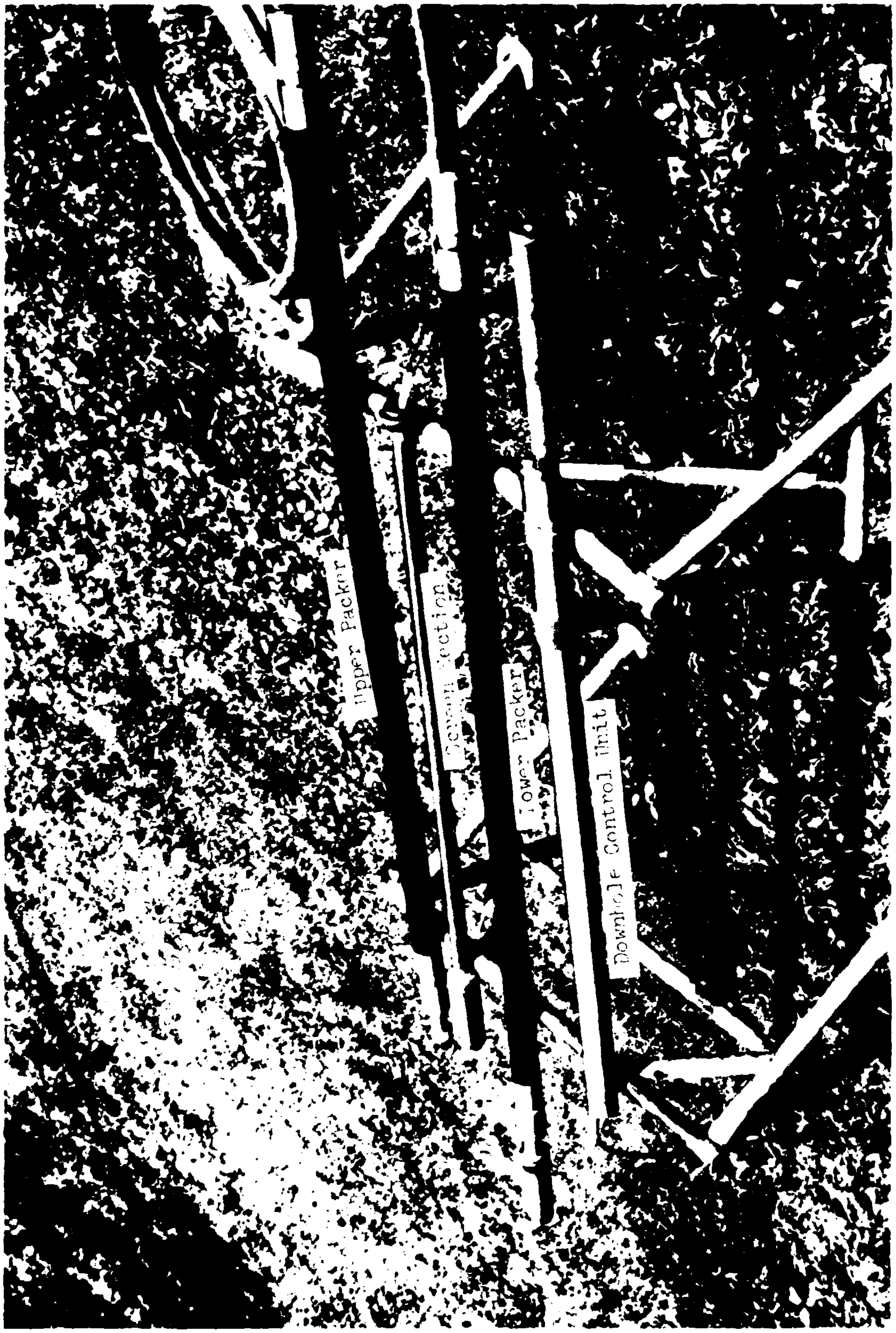


PLATE 1

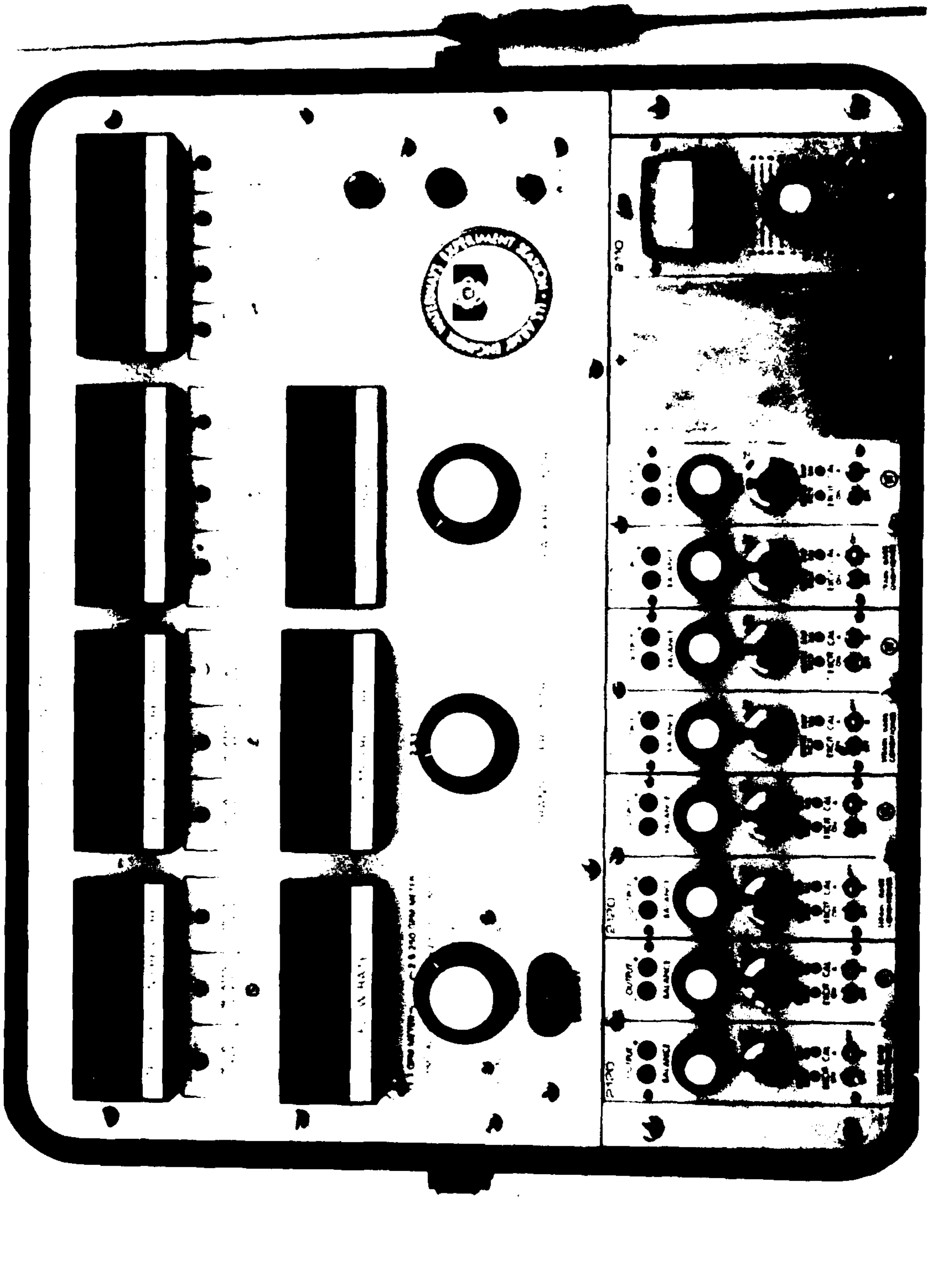


PLATE 2

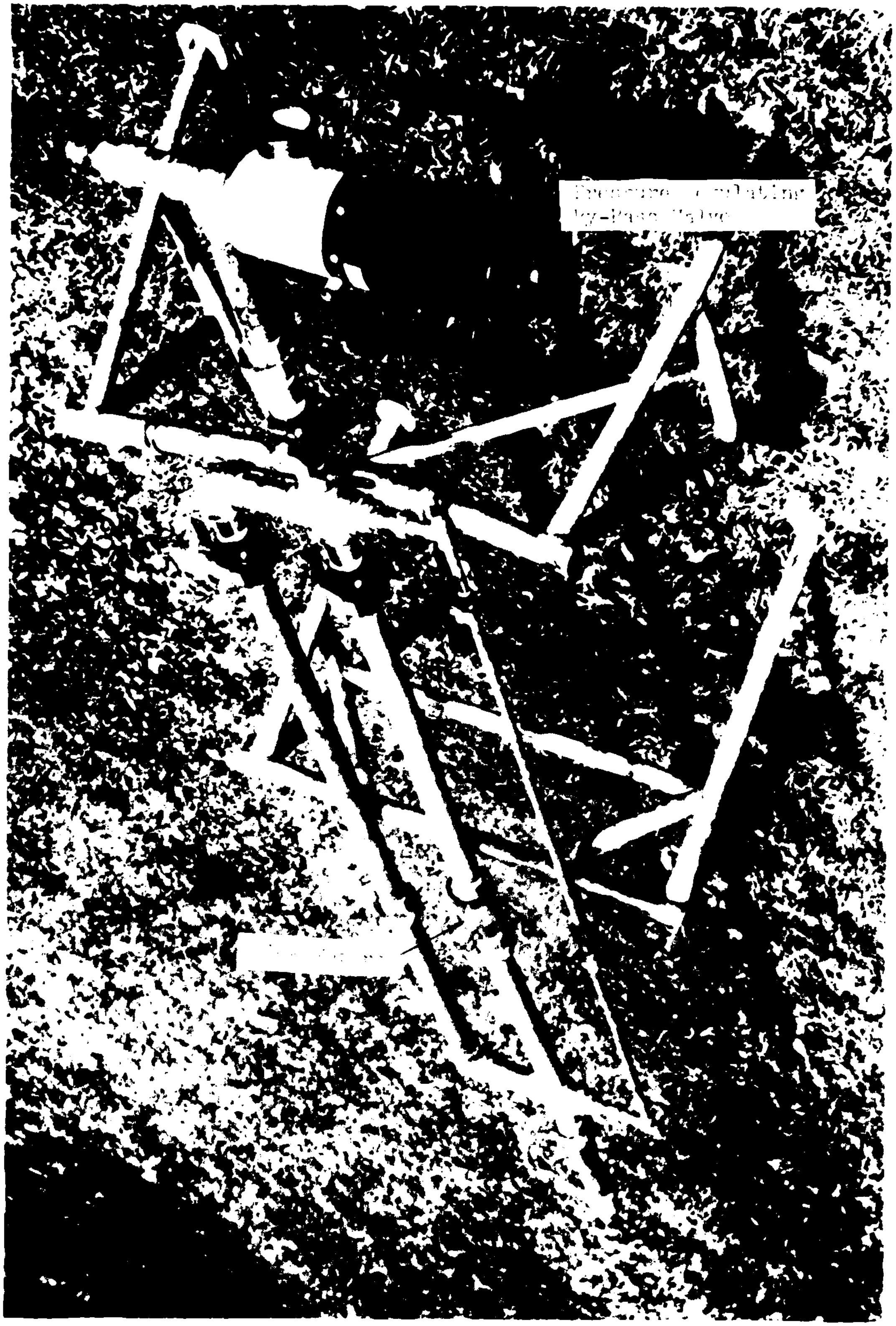


PLATE 3

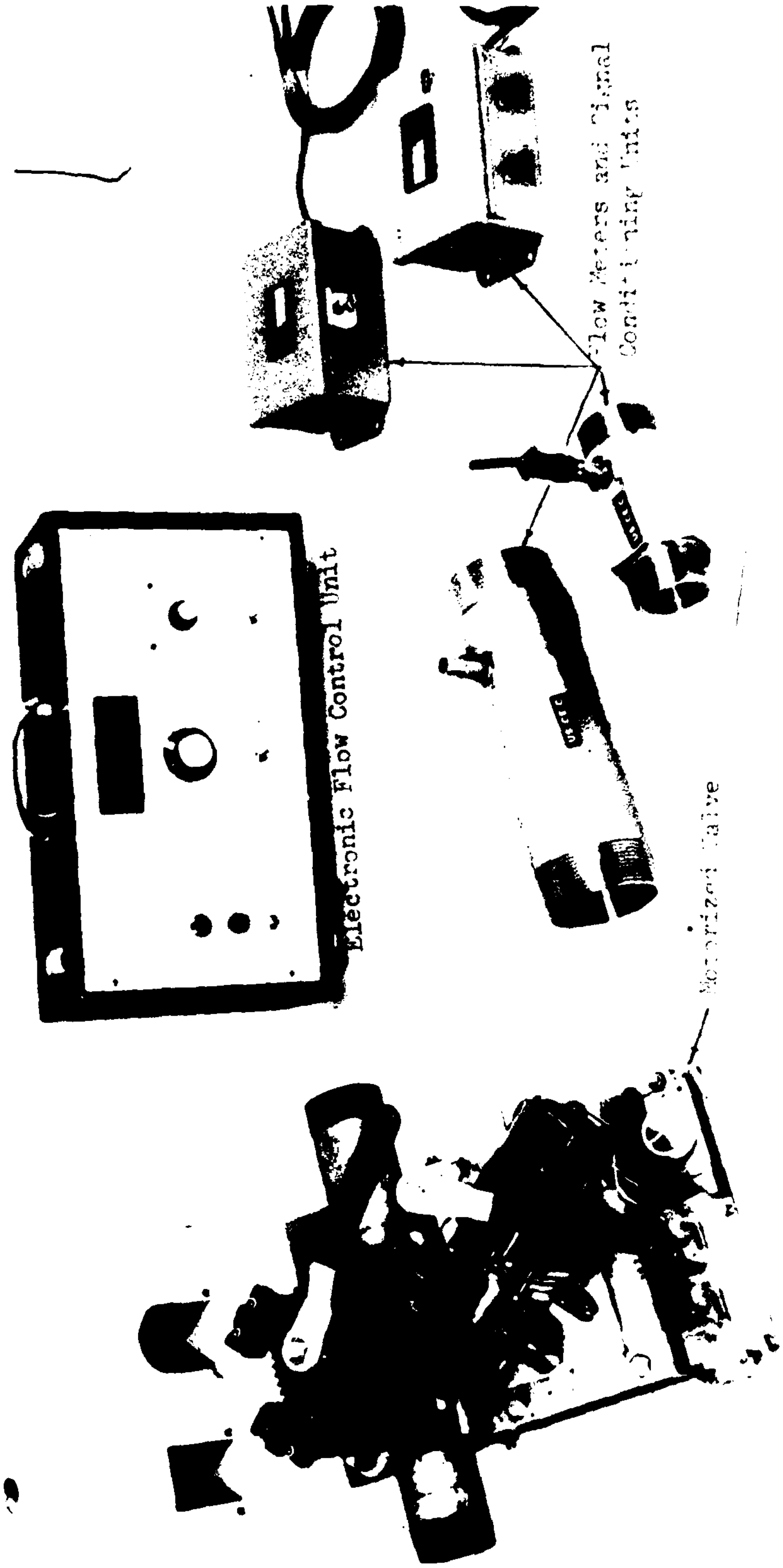

Flow Meters and Signal Conditioning Units
Electronic Flow Control Unit
Motorized Valve

PLATE 4

APPENDIX A: PRESSURE TEST METHODS

General Guidance

1. The following suggestions are made concerning drilling the borehole, pretest checkout of equipment, and testing precautions to promote a safe, reliable testing program.

Making the borehole

2. Pressure tests are commonly run in NX-size (3-in.-diam) boreholes, although this size is in no way required. Rotary drilling with water for cooling the drill bit and flushing drill cuttings from the hole is the normal method of making the hole. During drilling, the water pressure and loss rates should be monitored and recorded. High fluid pressures may cause hydraulic fracturing of the rock, which must be avoided. Sudden drops in the return flow rate indicates that a highly permeable or fractured zone has been penetrated. The drill string may chatter and vibrate when fractured rock is encountered, and if severe water loss occurs, the bit may become stuck. If the return flow rate suddenly increases after dropping off, it usually means the fissures through which the water loss was occurring have become plugged with drill cuttings, effectively sealing the borehole walls. The above information should be noted on the drilling log as an aid in selecting test depths and in interpreting data. Detailed core logs should be prepared by an experienced geologist during drilling. The hole should be pressure washed prior to testing to (a) remove remaining cuttings (which may clog the fissures) and (b) saturate zones to be tested above the water table. If single-packer tests are made sequentially as the hole is extended, there may be more likelihood of noting possible extenuating circumstances such as those above for at least two reasons:

- a. The test closely follows borehole extension so any unrecorded information which might affect test results can be recalled. This information may be lost or forgotten when tests are made sometime after completing the hole.
- b. Joints, fractures, or other high permeability zones may be more positively located and oriented when both the core and the log are available.

Borehole orientation and spacing

3. Boreholes for general site investigations are normally drilled vertically and pressure tested without regard to orientation or spacing of discontinuities in the rock. As information about the orientation, spacing, and relative importance of joints and fractures becomes available from boring logs, core samples, and initial pressure test results, additional strategically located and oriented borings should be made and tests which intersect the major identifiable features likely to influence seepage patterns and contribute to the overall flow rate should be conducted in these holes. Borehole TV or film camera surveys can be used to advantage to identify the frequency and orientation of joints and fractures and their use is recommended in selecting pressure test locations.

Test Setup

4. The following steps describe setup of the various components of the pressure test system, followed by step-by-step instructions for performing constant head, falling head, and air-pressure tests:

a. Set up surface mechanical equipment.

(1) Assemble the flow manifold as shown on Plate 3, including the regulating bypass valve.

(2) Close 90 deg valves, A, B, C, and D. (See Figure A1 for valve locations on the plumbing and wiring diagram.)

(3) Connect the flowmeter electrical cables and pump pressure pick-off line to the transducer. These lines are next connected to the small surface junction box.

(4) Connect the 1/4-in. nylon line between the regulating bypass valve and the injection pressure regulator on the air tank.

(5) Connect the water pump supply line, flexible hose, and downhole control unit as shown in Figure A1--a schematic of the flow manifold, downhole unit, and plumbing and wiring connections.

b. Make connections to surface electronic equipment.

(1) Check to make sure both AC power switches on the surface control unit are in the OFF position. Plate 2 shows the surface control unit. The switches are on the right side of the unit.

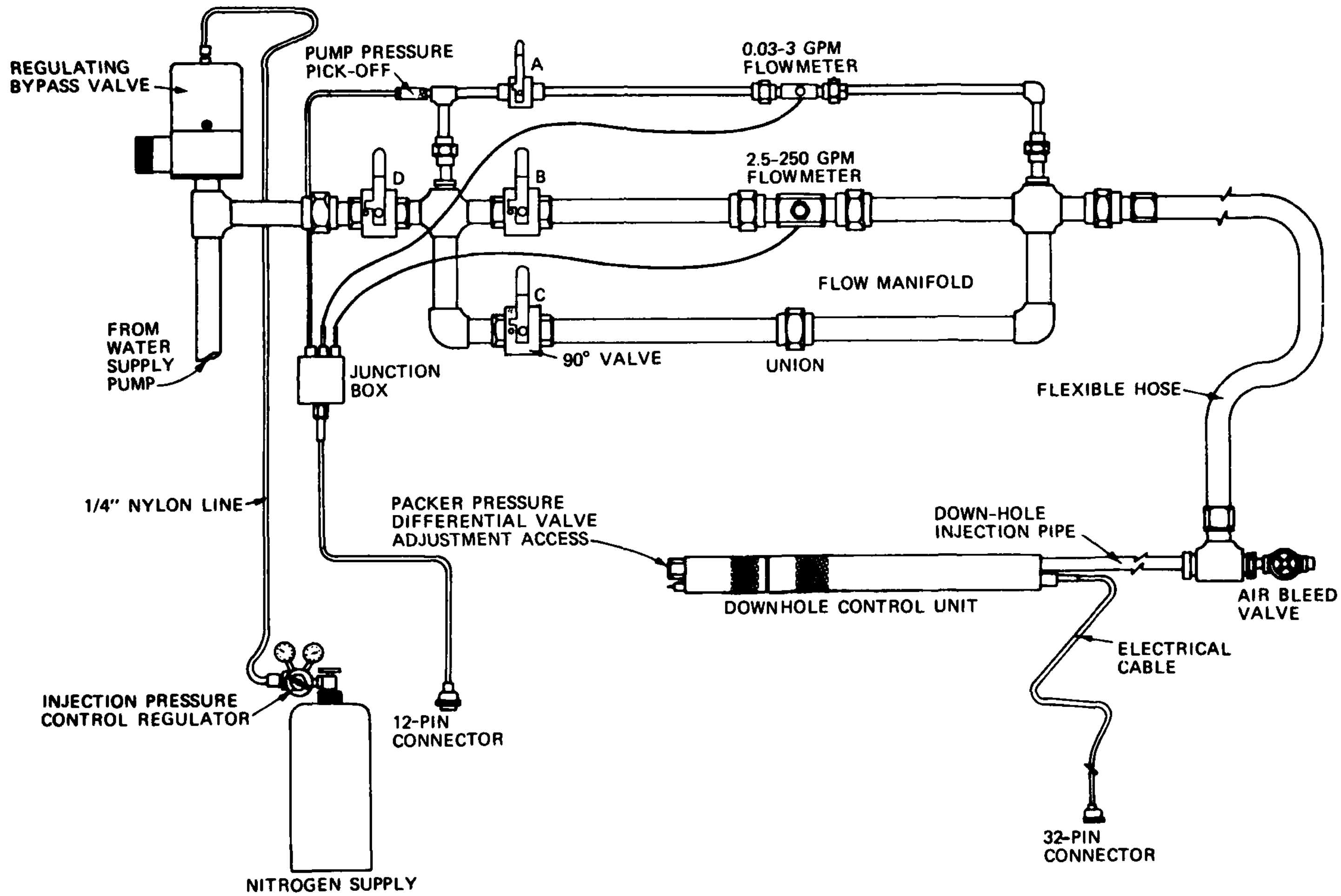


Figure A1. Schematic of flow manifold, downhole unit, and plumbing and wiring connections

(2) Connect all electrical cables to the Surface Control and Readout Unit. These include AC power, downhole control unit, and the flowmeter connection cable.

c. Calibrate pressure transducer.

(1) Switch the bridge excitation toggle switches to the OFF position on all STRAIN GAGE CONDITIONER units.

(2) Place the toggle switches marked CAL (also located on the conditioner units) to their center or OFF position. The CAL and STRAIN GAGE CONDITIONER switches are located along the bottom of the surface control unit front panel.

(3) Connect a twin-lead jumper cable from the EXTERNAL METER output of the conditioner power supply to the DVM INPUT located just below the flowmeter rotary selector switch.

(4) Place the flowmeter rotary switch in the EXT. DVM, position. (This connects the FLOWRATE meter to the DVM INPUT jacks.)

(5) Place the toggle switch on the conditioner power supply to the POWER position. (The red pilot lamp should illuminate.)

(6) Place the POWER switch on the main control unit to the ON position. All seven digital panel meters should illuminate.

(7) Set the CHANNEL selector switch on the Power Supply module to the AC position. The meter should read within the AC band.

(8) Turn the CHANNEL selector switch to DC; the meter should read on the DC check line.

(9) Turn the CHANNEL selector to channel 1. This connects the power supply meter and the flow rate meter to the number 1 strain gage conditioner, which is the conditioner located on the far left.

(10) Adjust the BRIDGE EXCT (using a small screwdriver) to read five volts on the FLOWRATE meter.

(11) Turn the CHANNEL selector switch to channel 2 and repeat step 10; adjusting the BRIDGE EXCT screw on conditioner 2 (second from the left).

(12) Turn the CHANNEL selector to channel 3. Repeat step 10, adjusting the BRIDGE EXCT screw on conditioner 3 (third from left). Repeat for channels 4 and 5. The remaining conditioners are spares and are not used.

(13) Use a small screwdriver to adjust the AMP BAL located on each of the conditioner units until both OUTPUT lamps are off or equally dimmed.

(14) Place all five EXCIT switches in the ON position.

(15) Allow five minutes warm-up time for the pressure transducer circuits to stabilize.

(16) Adjust the lockable BALANCE knobs on all five conditioner units to obtain zero readings on the corresponding meters. Note the OUTPUT lights should both be off or dimly lit. The display meters across the top of the control unit correspond in left to right order with the conditioner units, except conditioner number 5, which corresponds to the PUMP PRESSURE meter.

(17) Place the CAL toggle switches on all five conditioners to the "A" position.

(18) Adjust the lockable GAIN dials on the conditioner units to obtain the correct calibration number on each of the display indicators that correspond to the pressure transducer being used. Use the calibration chart provided (Figure A2) (Example: Channel No. 1 Transducer Ser. No. 245 Cal. No. 2909).

(19) Return the CAL toggle switches to their OFF position. The display indicators should return to zero. If not, repeat steps 16 through 19 on the channels indicating the zero shifts until steady zeros are obtained.

d. Calibrate flowmeter.

(1) The pressure injection test system will cover a wide range of flow rates (0.03 to 250 GPM), made possible by the use of two flowmeters (0.03 to 3 and 2.5 to 250 GPM, see Figure A1). The flowmeters are both plumbed into the flow manifold and valves control fluid flow through the flowmeters. The electrical output produced by fluid flowing through the flowmeters is nonlinear with respect to a change in flow. Because of the nonlinearity, several calibration numbers are provided with each flowmeter to cover the full range of flows.

(2) Turn the flowmeter selector switch to the 2.5-250 GPM CAL position.

(3) Use the flow calibration chart provided to determine the calibration number required for a flow of 100 GPM. This calibration is for initial setup only and will likely be changed during actual testing because of the changing pressure-flow relationship.

(4) Adjust the CAL ADJ located at the lower right of the flow selector switch until the meter matches the determined calibration number.

PRESSURE TRANSDUCER CALIBRATION

Transducer Serial No.	Amplifier Serial No.	Transducer Location	Bridge Excitation Volt	Cal. No.
245	25477	Downhole PT-1	5	2909
169	25477	Downhole PT-2	5	2901
334	25411	Downhole PT-3	5	3069
231	25411	Downhole Packer	5	2879
249	25441	Uphole Pump	5	2892
	25441			

FLOWMETER CALIBRATION

Flowmeter Serial No.	Size GPM	Hertz	GPM	Cal. No.	Hertz	GPM	Cal. No.
840816	0.03-3	6.29	0.06	11.353	21.09	0.075	5.495
840816	0.03-3	51.21	0.109	3.470	302.16	0.511	3.006
840816	0.03-3	603.67	1.02	3.005	970.81	1.658	3.004
840816	0.03-3	1262.08	2.159	3.015	1777.9	3.045	3.008
320441	250	12.05	2.13	244.8	50.56	8.90	289.3
320441	250	248.61	44.13	306.3	573.13	101.7	310.4
320441	250	727.94	129.2	311.6	955.21	169.7	313.1
320441	250	1213.02	215.8	313.2	1529.72	271.9	315.0
	CFM						
48192	750	11.3	13.9		24.3	24.0	
48192	750	130.0	119.1		249.7	227.8	
48192	750	453.4	409.1		821.2	750.1	
10349	16	62.0	0.60		334.0	2.4	
10349	16	663.0	4.8		985.0	7.2	
10349	16	1293.0	9.6		2169.0	16.8	

Figure A2. Pressure transducer calibration chart

(5) Turn the flow selector switch to 2.5-250 GPM METER position. The meter should read 0.6 or 0.7 GPM.

e. Adjust packer differential pressure valve.

(1) Check to make sure the injection pressure control regulator output reads zero.

(2) Start water pump. Water should flow freely from the large discharge pipe on the regulating bypass valve back to the supply reservoir.

(3) Refer to Figure A1 for steps 3 through 11. Open Valve D on the manifold.

(4) Slowly increase the regulating bypass valve pressure with the injection control regulator until a pump pressure of 100 PSI is indicated on the surface control unit digital meter.

(5) Open the air-bleed valve located at the junction of the flexible hose and downhole injection pipe.

(6) Raise the bleed valve higher than the rest of the equipment to allow the air to escape.

(7) Open Valve C on the manifold.

(8) Allow the air to bleed out of the system; then close the bleed valve.

(9) Use a 3/4-in. socket wrench with a short extension to adjust the differential pressure screw located just inside the discharge end of the downhole control unit (see Figure A1, packer pressure differential valve adjustment access) until water just starts to leak by the internal valve.

(10) Reduce the regulating bypass valve pressure until the flow of water from the downhole control unit stops completely.

(11) Slowly increase the bypass valve pressure until water once again begins to flow from the downhole control unit and note the pump pressure. If the indicated pressure is within ±5 PSI of 100 PSI, proceed to the next step. If not, repeat steps 9 through 11.

f. Assemble downhole tool.

(1) Assemble the downhole tool as shown in Figure 2 (main text).

(2) The tool must be assembled in two sections to avoid exceeding the hoisting height limit of the drill rig. The tool could also buckle if it were raised from the horizontal position entirely preassembled.

(3) The packers used with the downhole tool will shorten in length as they expand. Therefore, it is necessary to expand the top packer to the diameter of the borehole being tested. Measure the distance between the upper packer expansion slip collar and its junction box. Add this measurement to the test section length and record as in Figure A3. This sum is the actual test section length. The lower packer is fixed at the lower end of the test section so its contraction does not change the test section length.

(4) Use the lowering device provided to lower the bottom portion of the tool until the top of the screen section rests on the dogging plate at the collar of the hole. Secure this section at the hole collar and disconnect the lowering clamp.

(5) Raise the top portion of the tool over the hole and connect the two sections at the upper junction box.

(6) Lower the entire tool into the hole, adding injection pipe sections as needed to reach the deepest test depth in completed holes.

(7) As the tool is lowered, the electrical cable attached to the downhole control unit should be pulled taut and attached to the injection pipe using nylon wire ties at 10-ft intervals.

(8) After the tool has been placed at the deepest test depth, attach the flexible hose and bleed valve to the injection pipe.

(9) Open the bleed valve and slowly increase the injection pressure until the pump pressure reads 10 to 20 PSI. Water and air will discharge from the bleed valve.

(10) Continue bleeding the system until only water flows from the bleed valve. Close the valve.

(11) Zero all downhole pressure transducers and lock the balance knobs.

Constant Pressure Test Procedure

5. The following steps describe the procedure for performing constant pressure tests:

a. If the test is to start from the bottom of the borehole, only the top packer will be inflated for the first test. This test section length will be measured from the bottom of the inflated top packer to the bottom of the borehole.

b. Refer to Plates 2 and 3 to identify the component parts discussed in the following instructions. Place the PACKER

Type of Test:
Boring No.:
El. Top of Hole:
Borehole Diameter
Borehole Location:
Date:
Weather

Test Section Depth, ft	Test Section Length, ft	Test Section Pressure, psi	Pressure Below Packers psi	Pressure Above Packers psi	Packer Pressure, psi	Compressor or Pump Pressure, psi	Air Temp at Manifold	Air Temp in Test Section	Flow rate in Test Section, gpm

Figure A3. Pressure injection test data sheet

CONTROL switch located on the surface control unit to the 1-4 or center position. Check that the small red and green lights located under the PACKER PRESSURE meter are not illuminated. If the lights are not illuminated, the packer control valve motor is running in the downhole control unit. After approximately 30 sec the lights should illuminate, indicating the packer control valve is set to pressurize the upper packer and vent the lower packer.

c. Observe the PACKER PRESSURE meter and increase the pump pressure until the packer pressure reads approximately 80 PSI.

d. The FLOW RATE meter will indicate a small flow while the packer is inflating. Maintain this pressure until the flow drops to zero.

e. Increase the pump pressure while observing the test section pressure until a reading of 10 PSI is indicated. (The packer pressure should now read approximately 110 PSI.)

f. The test section pressure should not exceed 1 PSI/ft of overburden above the water table and 0.57 PSI/ft below the water table. Higher pressure could cause hydrofracturing in the test section. (Example: Assume material has a dry density of 144 lb/ft^3. The top of the test section is at a depth of 140 ft. The water table is at a depth of 30 ft. 140 ft - 30 = 110 x 0.57 = 62.7 PSI + 30 PSI = 92.7 PSI. The maximum test section pressure should not exceed 92 PSI.)

g. Increase the test section pressure to the maximum allowable predetermined pressure based on depth.

h. Maintain this pressure until the flow rate stabilizes (no change for a period of 2 or 3 min).

i. Maintain this pressure and check the indicated flow rate. If it is below 2.5 GPM, open Valve A on the manifold, close Valve B, and place the FLOW RATE selector switch to the 0.03-3 GPM position. If the flow rate is above 2.5 GPM, go to step m.

j. Note the indicated flow rate on the meter. Use the flow calibration chart (Figure A2) to determine the calibration number that corresponds to the indicated flow.

k. Change the FLOW RATE selector switch to the 0.03-3 GPM CAL position. Use a small screwdriver to turn the CAL ADJ screw until the selected calibration reading is indicated on the FLOW RATE meter.

l. Change the FLOW RATE selector switch back to the 0.03-3 GPM position and note the indicated flow. If the indicated flow falls within a new calibration setting, repeat steps j and k until the flow rate and calibration number correspond.

m. If after completing step l the flow rate is above 2.5 GPM, proceed with steps j through l using the 2.5-250 GPM range and corresponding calibration, rather than the 0.03-3 GPM position.

n. It is generally desirable to record a minimum of 10 pressure versus flow readings at each test location. Divide the maximum pressure by 10 to determine the subsequent readings, i.e., 100, 90, 80, etc. Repeat steps i through m for each pressure increment and record the pressure-flow data on a data sheet such as shown in Figure A3.

o. Return to step b under the "Constant Pressure Test Procedure" heading. Repeat steps b through n except while performing step b change the PACKER CONTROL switch to the 1-3 or left-hand position. This will inflate the bottom packer, reducing the test section length.

p. Place the PACKER CONTROL switch to the 2-4 or right-hand position. This will vent both packers. Reduce the pump pressure to zero and allow 5 min for the packers to deflate.

q. Raise the entire tool one test section length. If it is necessary to remove a section of injection pipe, bleed the system before starting a new test.

r. Repeat steps b through p for each section of borehole to be tested. Do not disconnect the downhole electrical cable between readings. If disconnection becomes necessary, allow a 5-min warm-up and rezero the meters before starting a new test.

Pressure Drop Test

6. Pressure drop tests are usually run after completing a constant head test, but may be run independently. The equipment needed is identical for both constant and falling head tests, with the addition of a stopwatch for timing the rate of pressure drop in the test section after the flow is shut off. Pressure drop tests may be performed above or below the water table, just like constant head tests. In tests above the water table, the test section should be saturated if possible before beginning the test. Otherwise, errors in interpreting data will result. The pressure drop test consists of the following steps:

a. Choose test depth. Usually it is desirable to start at the bottom of completed boreholes and proceed upwards.

b. Estimate limit pressure. See instructions under "Constant Pressure Test Procedure," subparagraph f.

c. Assemble downhole system according to instructions given under "Test Setup," subparagraph f.

d. Connect surface control and readout unit to downhole unit via electrical conductor cable.

e. Connect reservoir to pressure regulator and pump and gas cylinder. (See schematic, Figure A1.)

f. Attach water supply hose to injection line and test downhole system for leaks by inflating packers while the system is at the surface. Repair leaks and recheck. Deflate packers and detach water supply hose.

g. Zero and calibrate readout unit. (See specific instructions given under "Constant Pressure Test Procedure" for complete calibration details.)

h. Lower downhole unit into hole in two sections as explained under "Test Setup," subparagraph f. Attach sections of pressure injection pipe as needed to reach test depth. Use wire ties to attach electrical cable to injection pipe to prevent slack cable from becoming tangled up in the hole.

i. Recheck zero and adjust, if necessary.

j. Record depth to water in borehole, depth to the center of test section, and test section length.

k. Inflate packers.

l. Pressurize test section to desired constant test pressure. Caution: Maintain test pressure below effective overburden pressure to avoid possible uplift and fissure opening.

m. Shut off flow and record time.

n. Record elapsed time and excess head (pressure) remaining at several increments until equilibrium pressure is reached.

o. Repeat tests at approximately 10 different test pressures to check for nonlinear flow and consistent results.

p. Deflate packers. Allow 5 min for complete deflation.

q. Raise tool to next test depth and repeat steps i through o or remove unit from hole.

Note: It is important that the borehole should be pressure-washed before testing. The borehole walls and adjacent rock should be saturated prior to testing and all air should be purged from the test section before inflating the packers. Tests by Maini (1971) showed that the permeability determined for unsaturated rock could vary by over an order of magnitude from that of saturated rock. The gradient is higher in unsaturated rock, which allows flow into small fissures and pores and yields higher flow rates than tests on saturated rock. This fact is important for all water-pressure tests.

Air-pressure Test

7. The air-pressure test is essentially identical to the water-pressure test with one obvious difference; air is injected into the borehole rather than water. Air-pressure tests may be used when water is unavailable, or when testing in highly permeable material where the flow rate required to pressurize the test section cannot be maintained with water.

8. If the borehole is drilled with water, it should be allowed to dry before testing to avoid possible adverse effects from moisture absorbed on the borehole walls. Air-pressure tests should not be performed below the water table because of the uncertainty associated with assessing compressible gas flow through a water-saturated media. Air-pressure tests require the use of an air compressor with a recommended capacity of 350 cfm in addition to the equipment needed for water-pressure tests. The water reservoir is replaced by the air compressor. In addition, temperature-sensing transducers are required in the flow manifold and in the test section to permit the weight flow rate to be determined. The flowmeters must also be changed.

9. Steps required to execute an air-pressure test are listed below:

a. Choose test depth and estimate limit pressure.

b. Assemble downhole system. See instructions under "Test Setup," subparagraph f.

c. Connect surface control and readout unit to downhole unit with electrical conductor cable.

d. Connect air compressor to pressure regulator and gas cylinder.

e. Attach air-supply line to injection line and test downhole unit for leaks by pressurizing packers. Joints may be tested by applying soapy water and checking for bubbles. Repair any leaks and recheck. Deflate packers and detach supply line.

f. Zero and calibrate readout unit. (See calibration instructions given under "Constant Pressure Test Procedure.")

g. Lower downhole unit into hole. See instructions given under "Test Setup," subparagraph f. Attach sections as needed to reach desired test depth. Use wire ties to tie conductor cable to injection line to prevent fouling.

h. Recheck zero and adjust if necessary.

i. Record depth to center of test section and test section length.

j. Inflate packers.

k. Pressurize test section to desired constant test pressure and take readings of temperature, pressure, and flow rate in the test section and at the manifold until flow rate stabilizes. Maintain test pressure below effective overburden pressure to avoid possible uplift and fissure widening. If pressure drop test is to be run, go to step l; otherwise, go to step n.

l. Shut off air supply and record time.

m. Record elapsed time and pressure in the test section at several time increments until pressure returns to equilibrium.

n. Repeat test at several different pressures at same location to check for nonlinear flow and consistent results.

o. Deflate packers and raise unit to next test depth and repeat test or remove from hole.

Reporting Results

10. Numerous cases exist in the literature where pressure test results were used to estimate seepage patterns and quantities, yet test equipment and procedures and field conditions were poorly documented.

The following information should be obtained during the general investigation and testing program and included in the report:

a. Weather conditions and date.

b. Boring number and location and method of drilling and sampling and description of borehole washing procedure used.

c. Graphic boring log, showing joint and fracture orientation, frequency, and condition, and photographs of the core.

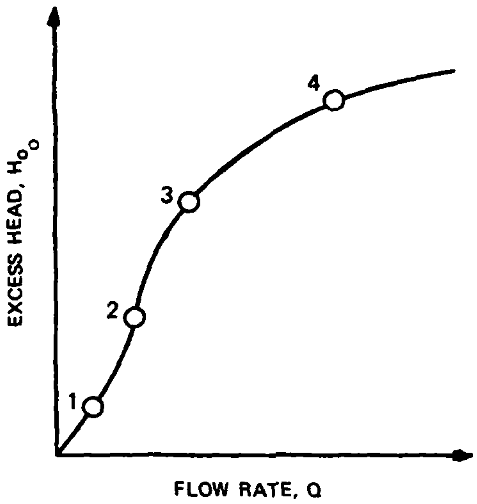
d. Geological cross sections of area of interest.

e. Pressure test section length and depth. Record depth from hole collar to center of test section. Record length between inflated packers.

f. Description of test equipment and methods used and any unusual conditions.

g. Test results should be recorded on a data sheet such as shown in Figure A3 and should include type of test (air; or water-pressure, constant head, or pressure drop), depth to water table, and how determined. The test data will include test section length and depth, flow rate, test section pressure, pressure above packer, pressure below packer, packer pressure, pump pressure, and hole diameter. Pressure and flow rate should be recorded and plotted during the test. For air-pressure tests, temperature at the surface and in the test section should be recorded to correct volume flow rates.

h. A log-log plot of excess head, H_o, versus flow rate, Q, should be prepared by plotting each pressure and flow rate increment at the same location to check for turbulent or nonlinear flow. A typical plot is shown in Figure A4 and a qualitative explanation of what may be happening downhole is offered for each distinct zone of the curve.



ZONE 1 - LINEAR LAMINAR REGIME
ZONE 2 - TURBULENCE EFFECTS
ZONE 3 - TURBULENCE OFFSET BY FISSURE EXPANSION, OR PACKER LEAKAGE
ZONE 4 - PREDOMINANCE OF FISSURE EXPANSION OR PACKER LEAKAGE

Figure A4. Typical result of water pressure tests conducted at a series of increasing pressures (after Zeigler (1976))

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Bennett, Robert D.
  New pressure test for determining coefficient of permeability of rock masses / by Robert D. Bennett, Robert F. Anderson (Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station). -- Vicksburg, Miss. : The Station ; Springfield, Va. : available from NTIS, 1982.
  41, 16 p., 4 p. of plates : ill. ; 27 cm. -- (Technical report : GL-82-3)
  Cover title.
  "July 1982."
  Final report.
  "Prepared for Office, Chief of Engineers, U.S. Army under Civil Works R & D Work Unit 31561."
  Bibliography: p. 40-41.

  1. Boring. 2. Pressure. 3. Rocks--Permeability. I. Anderson, Robert F. II. United States. Army. Corps of Engineers. Office of the Chief of Engineers. III. U.S. Army Engineer Waterways Experiment Station.

Bennett, Robert D.
  New pressure test for determining coefficient : ... 1982.
(Card 2)

Geotechnical Laboratory. IV. Title V. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; GL-82-3.
TA7.W34 no.GL-82-3